Aerial Surveys in the Walla Walla River Basin

Thermal Infrared and Color Videography

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Report to:

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Final Report

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Introduction

In 2002, the Washington Department of Ecology (DOE) contracted with Watershed Sciences, LLC (WS, LLC) to conduct airborne thermal infrared (TIR) remote sensing surveys within the Walla Walla River Basin, WA. The objective of the project was to characterize the thermal regime of the selected river segments to support ongoing stream temperature assessments in the basin.

This report documents the methods used to collect and process the TIR images. This report also presents spatial temperature patterns derived through analysis of the imagery. Thermal infrared and associated color video images are included in the report in order to illustrate significant thermal features. An associated ArcView GIS[1] database includes all of the images collected during the survey and is structured to allow analysis at finer scales.

Methods

Data Collection

The TIR surveys of streams in the Walla Walla River basin were conducted from August 7-9, 2002 and included segments of the Touchet River, North Fork Touchet River, South Fork Touchet River, Wolf Creek, Yellowhawk Creek, and Mill Creek (Figure 1). The time and extent of each surveyed river segment are summarized in Table 1. The flights were timed to best capture maximum daily stream temperatures, which typically occur between 14:00 and 17:00.

Watershed Sciences, LLC deployed in-stream data loggers prior to the survey to ground truth (i.e. verify the accuracy) of the TIR data. In addition, WA DOE deployed seasonal data loggers at different points in the basin to continuously monitor stream temperatures. Five of the WA DOE loggers were used to facilitate the calibration of the TIR imagery on Yellowhawk and Mill Creeks. Meteorological data including air temperature and relative humidity were recorded using a portable weather station (*Onset*) located at Lewis and Clark State Park along the Touchet River near river mile 55.1 (Table 2). The in-stream data were assessed at the time the image was acquired, with radiant values representing the median of ten points sampled from the image at the data logger location. The parameters used to calibrate the TIR images were fined tuned to provide a best fit to the in-stream data.

Images were collected with TIR (8-12μ) and visible-band cameras attached to a gyro-stabilized mount on the underside of a helicopter. The two sensors were aligned to present the same ground area, and the helicopter was flown longitudinally along the stream channel with the sensors looking straight down. Thermal infrared images were recorded directly from the sensor to an on-board computer in a format in which each pixel contained a measured radiance value. The recorded images maintained the full 12-

[1] Geographic Information System

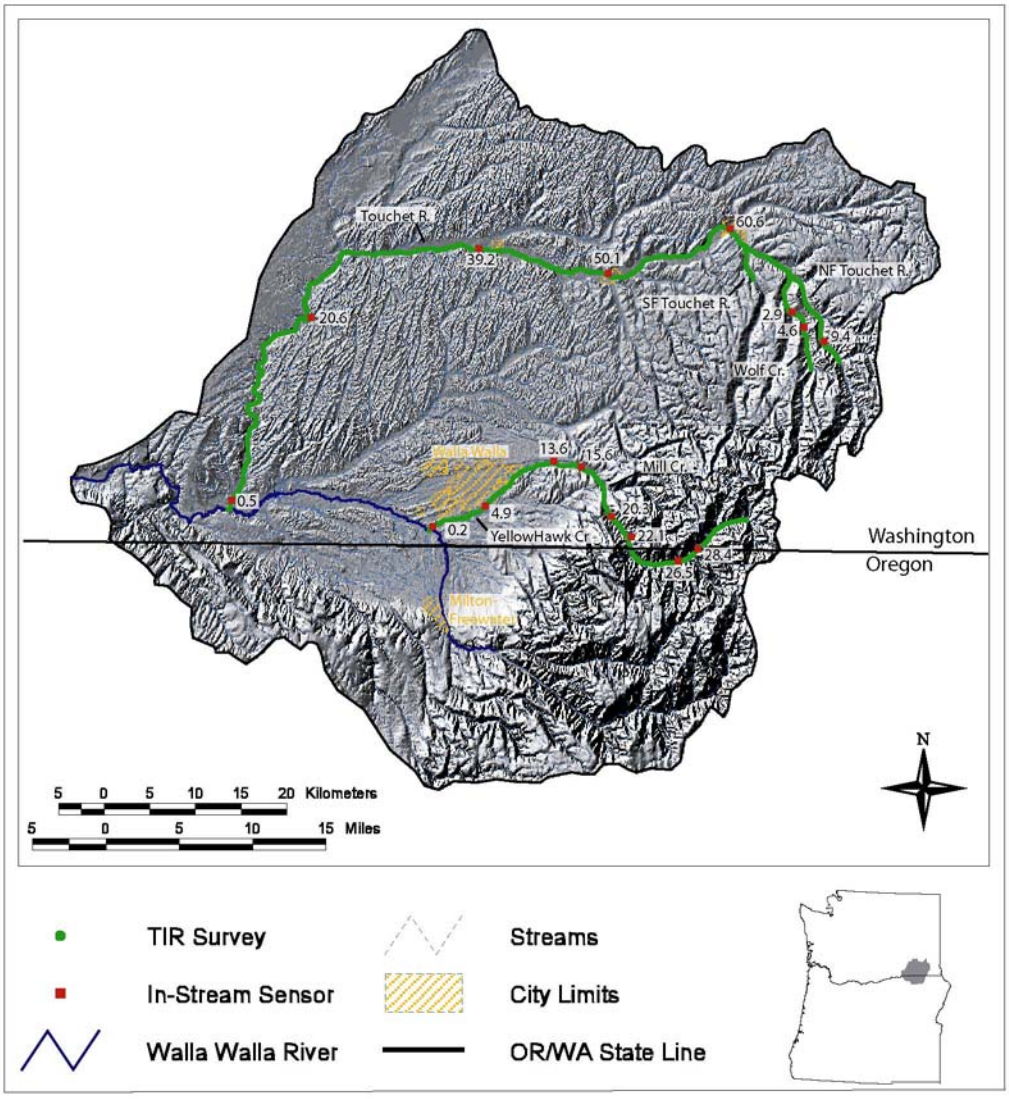


Figure 1 – Map showing the extent of the airborne TIR remote sensing survey conducted in the Walla Walla River basin from August 7-9, 2002. The map also shows the location of the in-stream sensors used to calibrate the TIR images labeled by river mile.

bit dynamic range of the sensor. The individual images were referenced with time and position data provided by a global positioning system (GPS).

A consistent altitude above ground level was maintained in order to preserve the scale of the imagery throughout the survey. The ground width and spatial resolution presented by the TIR image varied based on the flight altitudes. In general, the TIR images presented ground areas between 107 and 150 meters with spatial resolutions between 0.4 and 0.5 meters respectively (Table 1). All surveys were conducted in an upstream direction and the images were collected sequentially with approximately 40% vertical overlap.

Table 1 – Summary of river segments surveyed with TIR and color video in the Walla Walla River Basin from August 7-9, 2002.

Stream	Survey Date	Survey Time (24 hr)	Survey Extent	River Miles	Image Width Meter (ft)	TIR Image Pixel Size Meter (ft)
Yellowhawk Cr.	7-Aug	14:10-14:31	Mouth to Mill Cr.	8.5	107 (353)	0.4 (1.1)
Mill Cr.	7-Aug	14:10-15:28	Yellowhawk Cr. to rm 34.3	23.2	107 (353)	0.4 (1.1)
Touchet R.	8-Aug	13:37-15:22	Mouth to Forks	62.3	150 (494)	0.5 (1.5)
SF Touchet R.	8-Aug	15:22-15:27	Mouth to rm 2.5	2.5	107 (353)	0.4 (1.1)
NF Touchet R.	9-Aug	13:38-14:03	Mouth to rm 11.3	11.3	129 (423)	0.4 (1.3)
Wolf Cr.	9-Aug	14:09-14:25	Mouth to Whitney Cr.	7.8	129 (423)	0.4 (1.3)

Table 2 – Meteorological conditions for the dates and times of the TIR surveys that were recorded using a portable weather station located at Lewis and Clark State Park, WA.

Time (24 hr)	Air Temp ^{o}F	Air Temp ^{o}C	RH %
August 7, 2002			
14:00	78.0	25.6	29.6
14:30	78.7	26.0	26.3
15:00	76.6	24.8	30.0
15:30	75.2	24.0	31.0
August 8, 2002			
13:30	81.5	27.5	25.4
14:00	83.7	28.7	21.3
14:30	83.0	28.3	25.4
15:00	82.2	27.9	21.8
15:30	81.5	27.5	22.2
August 9, 2002			
13:30	88.7	31.5	20.9
14:00	89.5	31.9	17.9
14:30	91.0	32.8	17.9

Data Processing

Measured radiance values contained in the raw TIR images were converted to temperatures based on the emissivity of water, atmospheric transmission effects, ambient background reflections, and the calibration characteristics of the sensor. The atmospheric transmission value was modeled based on the air temperatures and relative humidity recorded at the time of the survey. The radiant temperatures were then compared to the kinetic temperatures measured by the in-stream data loggers. Atmospheric transmission calibrations were fine-tuned to provide the most accurate fit between the radiant and kinetic temperatures.

Once the TIR images were calibrated, they were integrated into a GIS in which an analyst interpreted and sampled stream temperatures. Sampling consisted of querying radiant temperatures (pixel values) from the center of the stream channel and saving the median value of a ten-point sample to a GIS database file (Figure 2). The temperatures of detectable surface inflows (i.e. surface springs, tributaries) were also sampled at their mouth. In addition, data processing focused on interpreting spatial variations in surface temperatures observed in the images. The images were assigned a river mile based on a 1:100k routed GIS stream coverage from the Environmental Protection Agency. The measures assigned from this coverage may not match stream measures derived from other map sources.

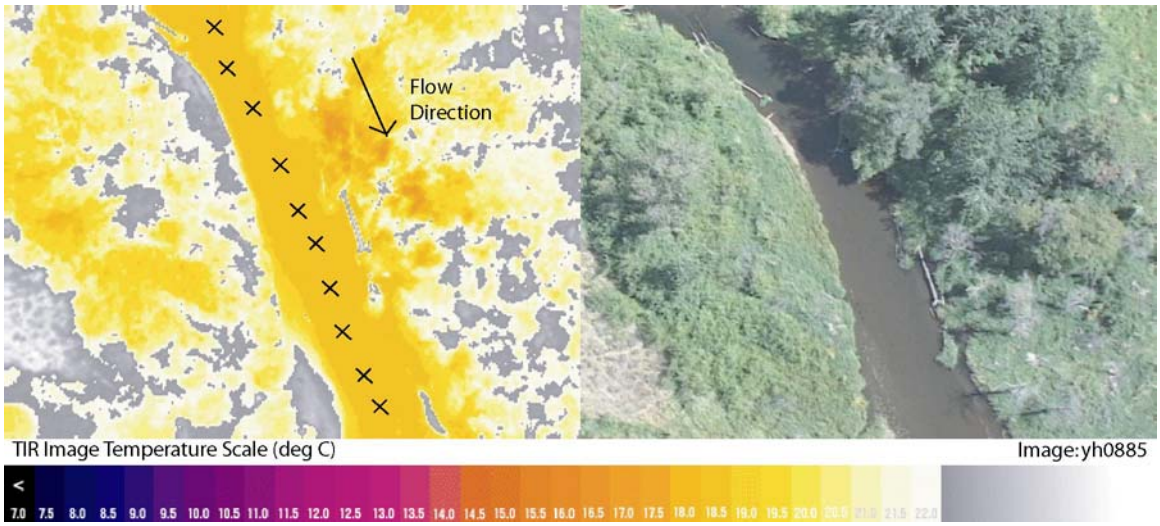


Figure 2 – TIR/color video image pair showing how temperatures are sampled from the TIR images. The black *X's* show typical sampling locations near the center of the stream channel. The recorded temperature for this image is the median of the sample points.

TIR Image Characteristics

Thermal infrared sensors measure TIR energy emitted at the water's surface. Since water is essentially opaque to TIR wavelengths, the sensor is only measuring water surface temperature. Thermal infrared data accurately represents bulk water temperatures where the water column is thoroughly mixed, however, thermal stratification can form in reaches that have little or no mixing. Thermal stratification in a free flowing river is inherently unstable due to variations in channel shape, bed composition, and in-stream objects (i.e. rocks, trees, debris, etc.) that cause turbulent flow. In the TIR images, indicators of thermal stratification include cool water mixing behind in-stream objects and/or abrupt transitions in stream temperatures.

Thermal infrared radiation received at the sensor is a combination of energy emitted from the water's surface, reflected from the water's surface, and absorbed and re-radiated by the intervening atmosphere. Water is a good emitter of TIR radiation and has relatively low reflectivity (approximately 4 to 6% of the energy received at the sensor is

due to ambient reflections). During image calibration, a correction is included to account for average background reflections. However, variable water surface conditions (i.e. riffle versus pool), slight changes in viewing aspect, and variable background temperatures (i.e. sky versus trees) can result in differences in the calculated radiant temperatures within the same image or between consecutive images. The apparent temperature variability is generally less than 0.6°C (Torgersen et al. 2001). However, the occurrence of reflections as an artifact (or noise) in the TIR images is a consideration during image interpretation and analysis. In general, apparent stream temperature changes of < 0.6°C are not considered significant unless associated with a point source.

Results

Thermal Accuracy

The average absolute difference between the kinetic temperatures recorded by the in-stream data loggers and the radiant temperatures derived from the TIR images for all in-stream locations was 0.4°C (Table 3). This value was within the desired accuracy (< 0.5°C) for the TIR surveys and was consistent with TIR surveys conducted in the Pacific Northwest over the past five years (Torgersen, 2001). On Yellowhawk and Mill Creeks, temperatures differences varied from –0.5°C to 0.7°C, a range of 1.2°C. The radiant temperatures were warmer than recorded temperatures for the two in-stream points on Yellowhawk Creek while radiant temperatures were cooler for 4 of the 6 in-stream locations on Mill Creek. These differences most likely reflect spatial variability in the atmospheric and background conditions as the survey progressed up Yellowhawk and Mill Creeks. In the Touchet River, absolute differences of -0.5°C to 0.3°C were observed between radiant and kinetic temperatures, which fell within the desired accuracy for the TIR surveys. The N.F. Touchet and Wolf Creek were both surveyed within a 35-minute time span and were calibrated using the same parameters. On these two streams, the differences between the radiant and kinetic temperatures ranges between –0.4 and 0.4°C.

Temporal Differences

Figure 3 shows in-stream temperature variations at a single location on Mill Creek and at a single location on the Touchet River during the TIR remote sensing survey. On Mill Creek at river mile 22.1, daily maximum stream temperatures were recorded between 13:30 and 14:30 and the TIR was conducted between 14:10 and 15:30. At this location stream temperatures decreased by 0.6°C during the time span of the survey. At river mile 60.7 on the Touchet River, the TIR survey occurred just prior to the daily maximum stream temperature, which was recorded between 15:20 and 18:00. At this location stream temperatures changed by 1.0°C during the time span of the TIR survey. Temporal plots are not provided for the other surveyed streams since the duration of the flights were less than 30 minutes.

Table 3 – Comparison of ground-truth water temperatures (Kinetic) with the radiant temperatures derived from the TIR images.

Stream	Sensor	Image Frame	River mile	Time 24 hr	Kinetic °C	Radiant °C	Difference (K-R)
August 7, 2002 - Yellowhawk Creek and Mill Creek							
Yellowhawk Cr	WS	yh0157	0.2	14:11	17.2	17.6	-0.4
Yellowhawk Cr	DOE	yh0487	4.9	14:22	17.6	18.1	-0.5
Mill Cr	WS	yh0961	13.6	14:39	19.5	19.0	0.5
Mill Cr	DOE	yh1154	15.6	14:47	19.0	18.3	0.7
Mill Cr	DOE	yh1465	20.3	14:57	16.7	16.1	0.6
Mill Cr	WS	yh1585	22.1	15:02	14.9	14.3	0.6
Mill Cr	DOE	yh1895	26.5	15:15	10.5	10.6	-0.1
Mill Cr	DOE	yh2009	28.4	15:17	9.7	9.7	0.0
August 8, 2002 – Touchet River and S.F. Touchet River							
Touchet R	WS	touc3031	60.6	15:19	19.7	19.9	-0.2
Touchet R	WS	touc2467	50.1	15:01	20.9	21.4	-0.5
Touchet R	WS	touc1911	39.2	14:42	22.2	21.9	0.3
Touchet R	WS	touc0983	20.6	14:10	21.7	21.5	0.2
Touchet R	WS	touc0049	0.5	13:39	21.6	21.3	0.3
August 9, 2002 – N.F. Touchet River and Wolf Creek							
Touchet R	WS	nftt0082	60.6	13:41	19.4	19.0	0.4
NF Touchet R	WS	nftt0642	9.4	13:59	15.8	15.9	-0.1
Wolf Cr	WS	wlf0190	2.9	14:16	15.3	15.7	-0.4
Wolf Cr	WS	wlf0285	4.6	14:19	15.3	15.0	0.3

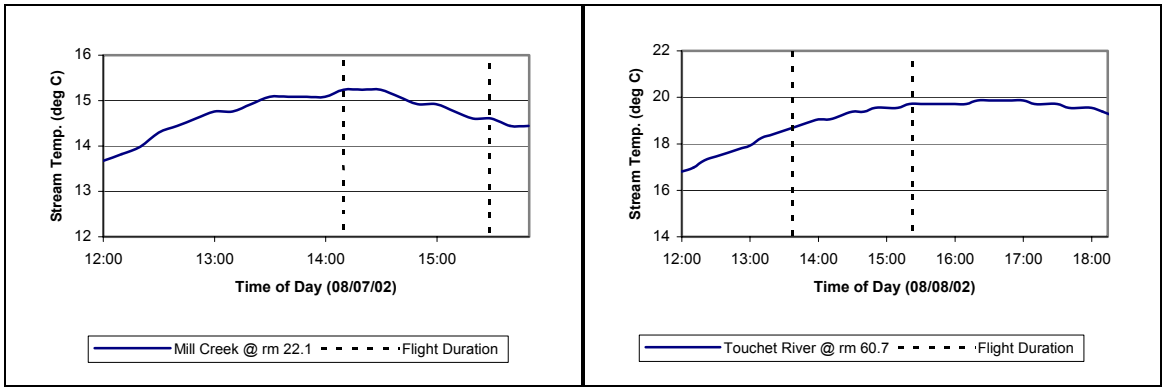


Figure 3 – Stream temperature variation and time of TIR remote sensing over flight for a sensor location on Mill Creek (*left*) on August 7, 2002 and for Touchet River (*right*) on August 8, 2002.

Yellowhawk Creek

Yellowhawk Creek had narrow channel widths relative to pixel size and at many locations the riparian vegetation masked the full width of the stream (Figure 4). However, the stream surface was visible at regular intervals throughout the survey, which allowed consistent temperature sampling. The median temperatures for each sampled image of Yellowhawk Creek were plotted versus the corresponding river mile (Figure 5).

Stream temperatures in Yellowhawk Creek showed an overall cooling trend in the downstream direction. At the diversion from Mill Creek (river mile 8.4), stream temperatures in Yellowhawk Creek were ≈20.4^{o}C. At river mile 7.8, Yellowhawk Creek splits into two channels that rejoin at river mile 6.8. The flight followed the right channel (*looking upstream*) because the left channel was indistinct with no visible surface water. Although, the right channel was more distinct, surface water was only intermittently visible through the riparian canopy. From the split in the channels downstream to river mile 6.0, stream temperatures appeared to cool by ≈2.0^{o}C. No surface water inflows were detected (*or mapped*) through this reach, which suggests subsurface discharge as a potential source of cooling. Stream temperatures also appeared to cool between river miles 4.5 and 4.1 (-1.1^{o}C) and between river miles 3.5 and 2.2 (-1.5^{o}C). Although no surface water inflows were detected through this reach, the USGS 7.5' topographic maps show Caldwell Creek, Russell Creek, and Cottonwood Creek entering Yellowhawk Creek between river miles 4.5 and 2.2. This suggests subsurface flow traveling through the tributary channels as a possible source of cooling. Riparian vegetation masked the confluence of each of these tributaries making it impossible to determine from the airborne imagery if the tributaries were carrying any surface water.

Figure 4 – Ground level photograph (*left*) and airborne color video image (*right*) showing the same location on Yellowhawk Creek at river mile 0.2. The ground level photo was taken looking downstream from the bridge. The two images illustrate stream width and riparian vegetation conditions characteristic of Yellowhawk Creek.

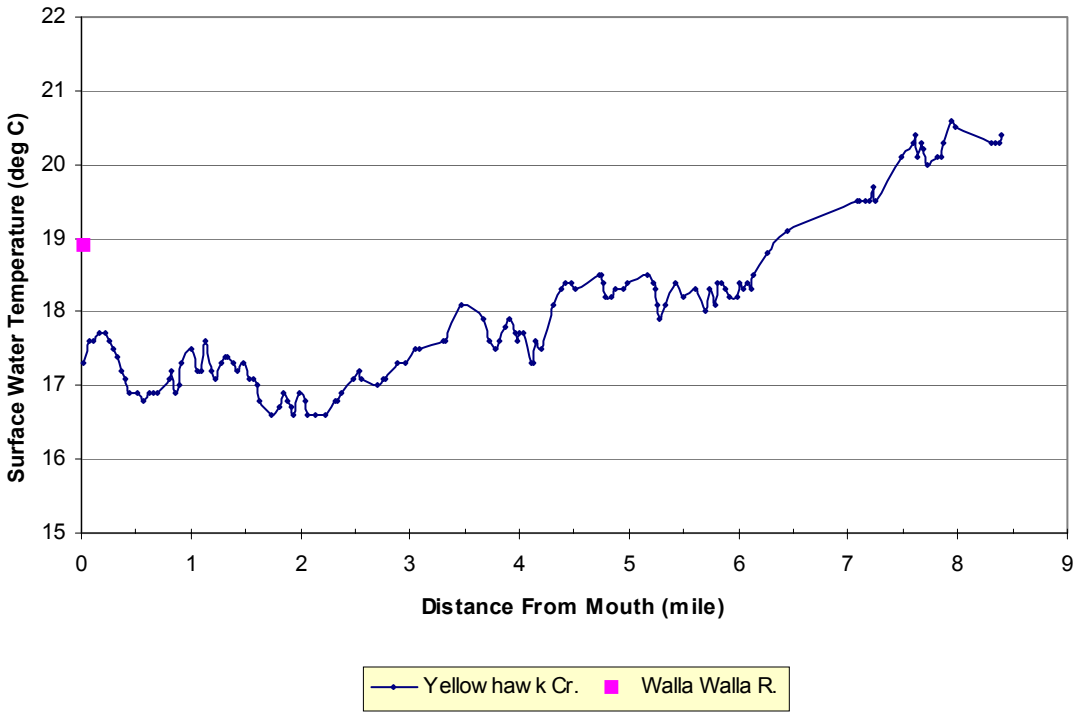


Figure 5 - Median channel temperatures versus river mile for Yellowhawk Creek, WA as well as the temperature of the Walla Walla River at the confluence of the two.

Mill Creek

The median temperatures for each sampled image of Mill Creek were plotted versus the corresponding river mile (Figure 6). The plot also contains the median temperature of all surface water inflows (e.g. tributaries, surface springs, etc.) that were visible in the imagery. In addition, the plot shows the location of detected tributaries that were not sampled during the processing of the TIR images due to masking by the forest canopy. These tributaries were assigned the temperature of Mill Creek in order to indicate their location on the longitudinal temperature profile. Sampled tributaries are listed sequentially by river mile in Table 4.

Mill Creek shows a pattern of downstream warming gaining ≈12.6°C over the 23.0-mile survey. Stream temperatures were ≈7.6°C near the headwaters (river mile 34.2), but dropped to ≈6.5°C at river mile 33.0. Three tributaries, including the Green Fork, enter Mill Creek near this location and are most likely the source of cooling. Stream temperatures increase consistently downstream reaching 15.0°C at river mile 21.4. Six tributaries were detected through this reach, however not enough surface water was visible through the canopy to get an accurate temperature sample at the tributary mouth. Between river mile 21.4 and the diversion dam (river mile 11.2), stream temperatures increased from 15.0°C to 20.2°C. This reach was characterized by a number (21 sampled) of small springs and seeps, which emerged from within the channel floodplain and created

localized cool areas (Figure 7). Since many of the springs occur as seeps near the stream surface, the sampled temperatures may represent a partially mixed condition and actual subsurface temperatures might be slightly cooler.

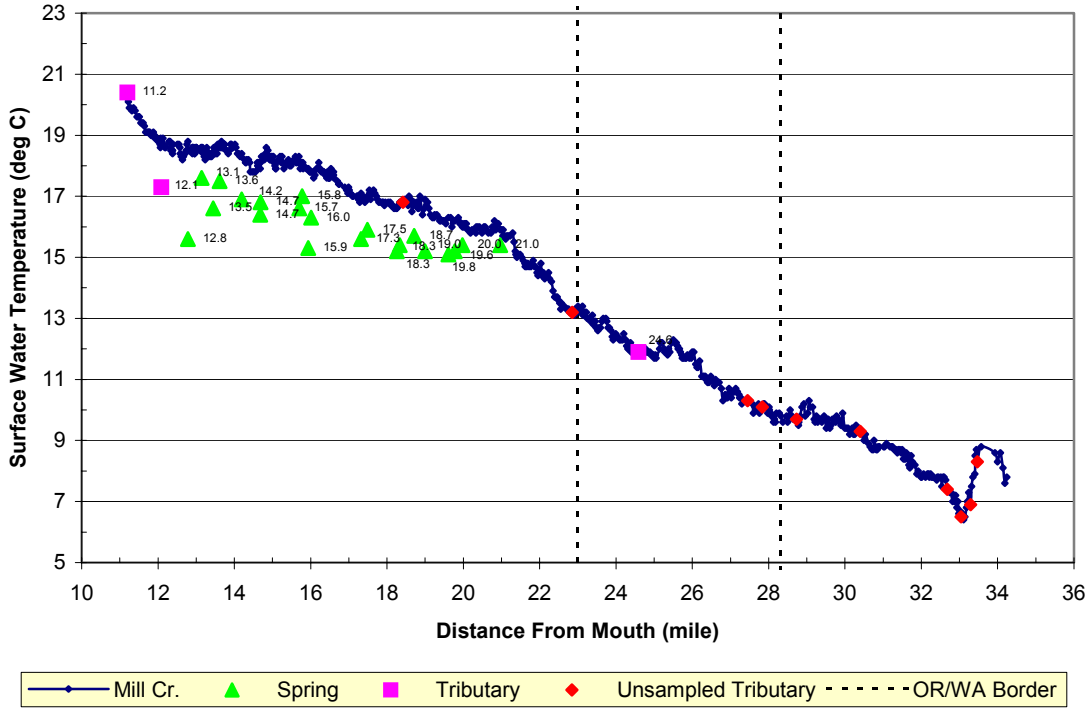


Figure 6 - Median channel temperatures versus river mile for Mill Creek, WA along with the location of surface water inflows including tributaries and springs. The plot also shows the location of detected tributaries that were not sampled.

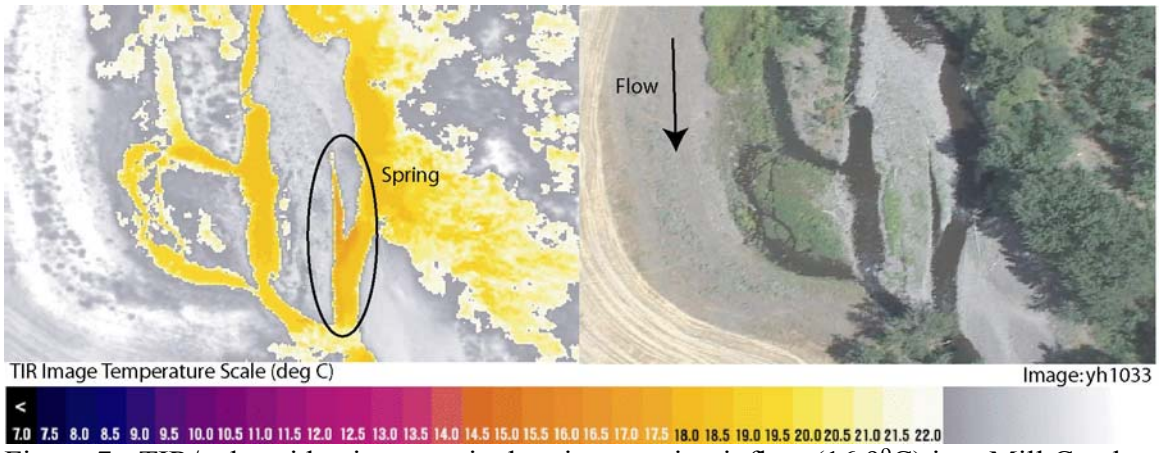


Figure 7 - TIR/color video image pair showing a spring inflow (16.9°C) into Mill Creek (18.4°C). *(frame: yh1033).* The seep occurring within the channel floodplain was characteristic of the springs sampled between river miles 21.4 and 11.2.

Table 4 – Tributary temperatures for Mill Creek, WA. RB = Right Bank, LB = Left Bank, looking downstream.

Tributary	Image	Km	Mile	Tributary °C	Mill Cr. °C	Difference trib-main
Yellowhawk Cr (LB)	yh0755	18.0	11.2	20.4	20.2	0.2
Unnamed Trib (LB)	yh0813	19.5	12.1	17.3	18.8	-1.5
Spring (LB)	yh0898	20.6	12.8	15.6	18.8	-3.2
Spring (LB)	yh0926	21.2	13.1	17.6	18.6	-1.0
Spring (LB)	yh0952	21.6	13.5	16.6	18.4	-1.8
Spring (RB)	yh0966	21.9	13.6	17.5	18.6	-1.1
Spring (LB)	yh1033	22.8	14.2	16.9	18.4	-1.5
Spring (RB)	yh1066	23.6	14.7	16.4	17.9	-1.5
Spring (LB)	yh1067	23.6	14.7	16.8	18.1	-1.3
Spring (LB)	yh1156	25.3	15.7	16.6	18.1	-1.5
Spring (RB)	yh1163	25.4	15.8	17.0	18.0	-1.0
Spring (LB)	yh1175	25.7	15.9	15.3	17.9	-2.6
Spring (LB)	yh1181	25.8	16.0	16.3	17.8	-1.5
Spring (LB)	yh1276	27.9	17.3	15.6	17.1	-1.5
Spring (RB)	yh1289	28.1	17.5	15.9	16.9	-1.0
Spring (LB)	yh1339	29.4	18.3	15.2	16.6	-1.4
Spring (LB)	yh1344	29.5	18.3	15.4	16.8	-1.4
Spring (LB)	yh1366	30.1	18.7	15.7	16.8	-1.1
Spring Complex (LB)	yh1384	30.6	19.0	15.2	16.9	-1.7
Spring (LB)	yh1422	31.6	19.6	15.1	16.3	-1.2
Spring (LB)	yh1433	31.8	19.8	15.2	16.2	-1.0
Spring (LB)	yh1445	32.2	20.0	15.4	16.0	-0.6
Spring Complex (RB)	yh1510	33.7	21.0	15.4	15.9	-0.5
Henry Canyon Cr (LB)	yh1754	39.6	24.6	11.9	11.9	0.0

Touchet River

The median temperatures for each sampled image of the Touchet River were plotted versus the corresponding river mile (Figure 8). The plot also contains the median temperature and name of all surface water inflows (e.g. tributaries, surface springs, etc.) that were visible in the imagery.

Stream temperatures in the Touchet River were ≈19.0°C at the confluence of the North and South Forks (river mile 61.2) and warmed in the downstream direction reaching 21.2°C at river mile 53.6. Between river mile 53.6 and 49.2, stream temperatures remained relatively constant (±0.4°C), but then showed a slight decrease (≈0.6°C) near the confluence of Coppei Creek (river mile 49.0). Over the next 4 miles, stream temperatures increased by ≈2.5°C reaching ≈22.3°C at river mile 44.2 before decreasing to ≈21.0°C at

river mile 40.0. A small spring and a cooler side channel were sampled through this reach and the river was characterized in several areas by multiple channels and gravel bars (Figure 9). Channel characteristics and the observed cool seeps suggest that hyporheic flow is a possible pathway of cooling in this reach.

Stream temperatures increased downstream of river mile 40.3 reaching a maximum of 23.6°C at river mile 32.0. Stream temperatures then decreased by 2.6°C over the next 6 miles. No surface water inflows were sampled through this reach. Review of the USGS 7.5' topographic map shows that the cooling trend begins near the downstream end of the Touchet Valley where the river transitions from an open valley to a more confined canyon. The change in morphology suggests that subsurface flow may be forced into the stream channel resulting in an observed decrease in main stem temperatures.

Between river mile 26.0 and 6.0, water temperatures in the Touchet River showed an overall increase of 1.5°C with some local variability. No surface water inflows were sampled through this reach. Over the lower 6.0 miles, a higher degree of thermal variability was observed with surface temperatures varying between 20.2°C and 23.0°C. Review of the TIR images suggests that thermal stratification may contribute to the observed variations (Figure 10) behind the diversion at river mile 4.9. However, there were no additional signs of thermal stratification in the TIR images within the reach and the source of the observed variability could not be positively determined.

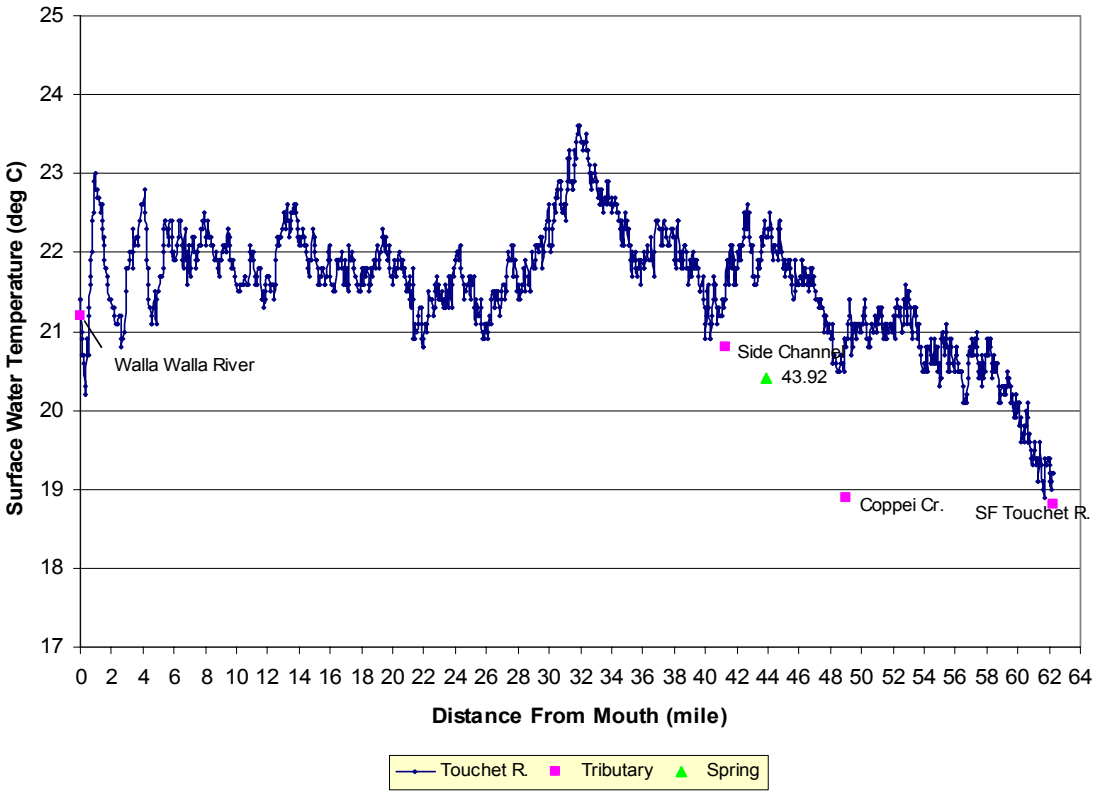


Figure 8 - Median channel temperatures versus river mile for the Touchet River, WA along with the name and location of sampled surface inflows.

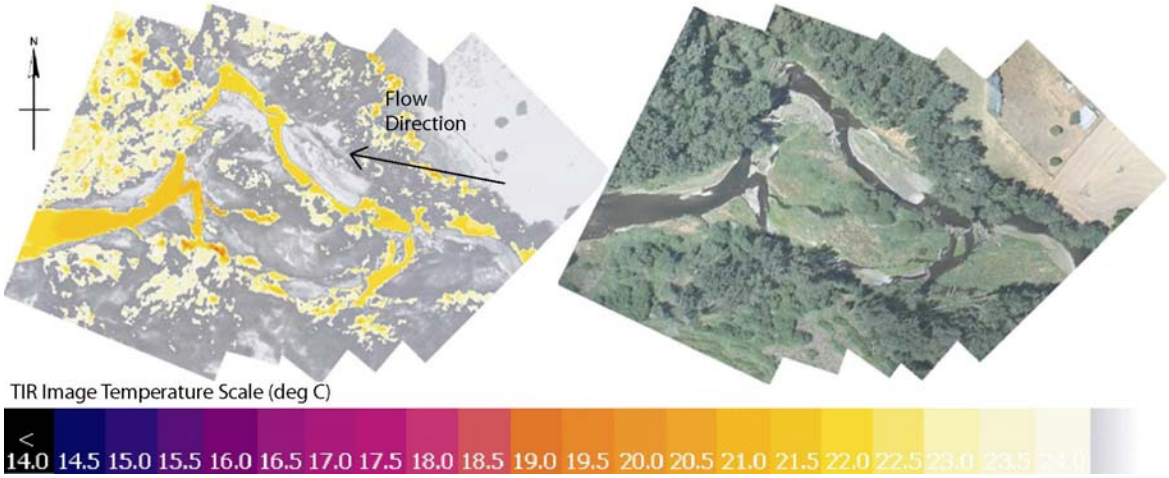


Figure 9 - TIR/color video image pair showing channel characteristics at river mile 41.2. A cooler side channel (20.8°C) on the left bank of Touchet River (21.4°C) may be the result of shallow sub-surface flow within the channel floodplain *(frames: touc2014-2019).*

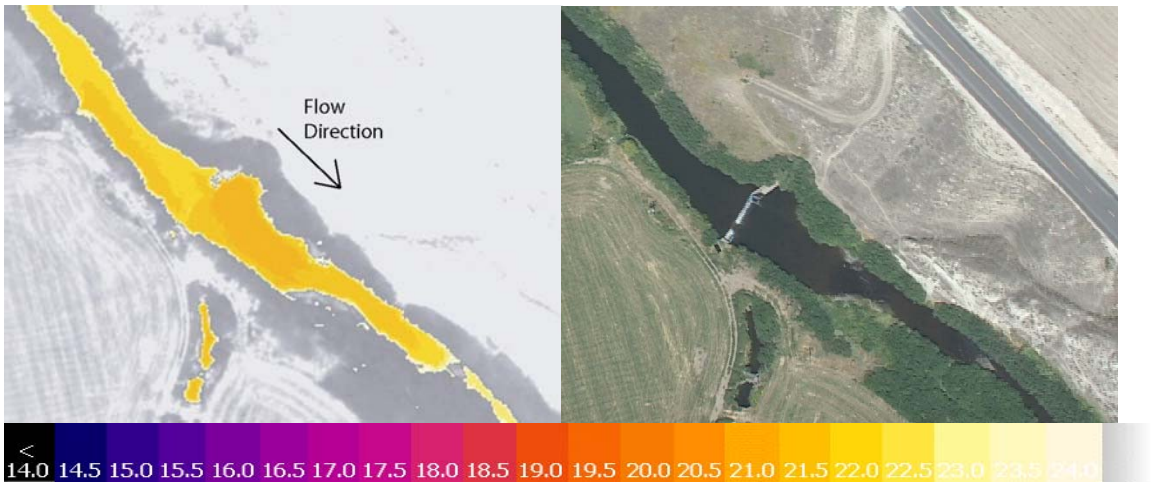


Figure 10 - TIR/color video image pair showing possible thermal stratification behind a diversion dam in Touchet River at river mile 4.9. Stream temperature downstream of the diversion is 20.8°C while the surface water temperature upstream of the dam was 21.5°C *(frame: touc0229).*

South Fork Touchet River

The median temperatures for each sampled image of the South Fork Touchet River were plotted versus the corresponding river mile (Figure 11). The plot also shows the location of two small springs that were detected and sampled during the analysis of the TIR images.

The SF Touchet River was surveyed from the mouth upstream to river mile 2.5. Stream temperatures in the SF Touchet River were ≈21.5°C (±0.4°C) between river mile 2.5 and 1.0. Stream temperatures decreased by ≈2.8°C was observed in the lower 1.0 miles of the SF Touchet River. Two small springs were observed near the mouth, which suggest sub-surface pathways as the source of cooling.

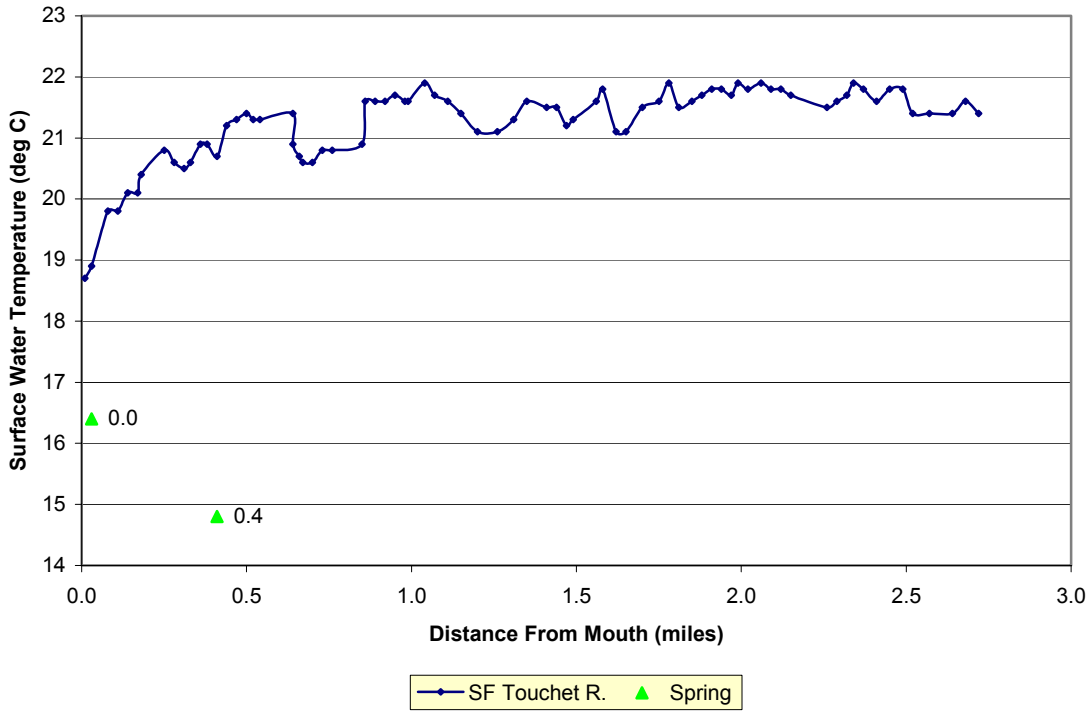


Figure 11 - Median channel temperatures versus river mile for the South Fork Touchet River, WA along with the location of sampled surface inflows.

North Fork Touchet River

The median temperatures for each sampled image of the NF Touchet River were plotted versus the corresponding river mile (Figure 12). The plot also contains the median temperature of all surface water inflows (e.g. tributaries, surface springs, etc.) that were visible in the imagery labeled by river mile. Sampled surface water inflows are listed sequentially by river mile in Table 5.

Stream temperatures were ≈14.6°C at the upstream end of the survey (river mile 11.5). Six cool water sources were sampled between river miles 10.7 and 11.2, which contributed to a decrease in main stem temperatures within this reach. From this point, stream temperatures increased steadily in the downstream direction reaching ≈18.5°C at river mile 5.5. Stream temperatures remained relatively constant at 18.4°C (±0.5°C) over the lower 5.5 river miles. Overall, 16 tributary and spring inflows were sampled through this reach. Twelve of these inflows were identified as springs or seeps and contributed water that was significantly (i.e. >= 0.5°C) cooler than the NF Touchet River. The six springs/seeps identified between the mouth and river mile 6.6 emerged within the channel floodplain and did not create major inflections in the basin scale temperature profile (Figure 13). However, the springs/seeps resulted in fine scale thermal variability in the stream and suggest that hyporheic exchanges may play a role in buffering stream temperature increases in the NF Touchet River.

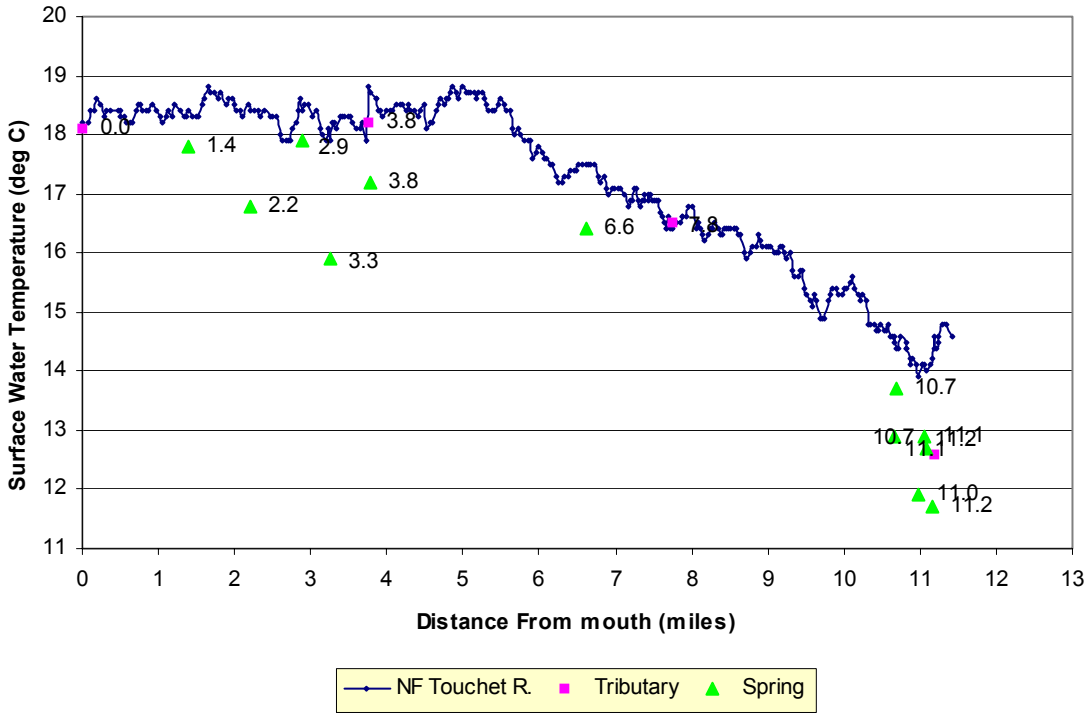


Figure 12 - Median channel temperatures versus river mile for the North Fork Touchet River, WA. Tributary and spring inflows are sampled by river mile.

Table 5 – Tributary temperatures for the NF Touchet River, WA. RB = Right Bank, LB = Left Bank looking downstream.

Tributary	Image	Km	Mile	Tributary °C	NF Touchet °C	Difference
Wolf Creek (LB)	nftt0153	0.0	0.0	18.1	18.2	-0.1
Spring (RB)	nftt0222	2.1	1.4	17.8	18.4	-0.6
Spring (LB)	nftt0261	3.4	2.2	16.8	18.4	-1.6
Seep (LB)	nftt0293	4.5	2.9	17.9	18.4	-0.5
Spring (LB)	nftt0312	5.1	3.3	15.9	17.9	-2.0
Wolf Creek (LB)	nftt0339	5.9	3.8	18.2	18.8	-0.6
Spring (LB)	nftt0340	6.0	3.8	17.2	18.7	-1.5
Spring (LB)	nftt0485	10.5	6.6	16.4	17.5	-1.1
Jim Creek (RB)	nftt0539	12.4	7.8	16.5	16.4	0.1
Spring (LB)	nftt0714	17.0	10.7	12.9	14.5	-1.6
Spring Complex (LB)	nftt0717	17.1	10.7	13.7	14.4	-0.7
Spring (RB)	nftt0735	17.6	11.0	11.9	13.9	-2.0
Spring (LB)	nftt0739	17.7	11.1	12.9	14.1	-1.2
Spring (RB)	nftt0740	17.7	11.1	12.7	14.0	-1.3
Spring (LB)	nftt0744	17.8	11.2	11.7	14.2	-2.5
Lewis Creek (RB)	nftt0745	17.9	11.2	12.6	14.6	-2.0

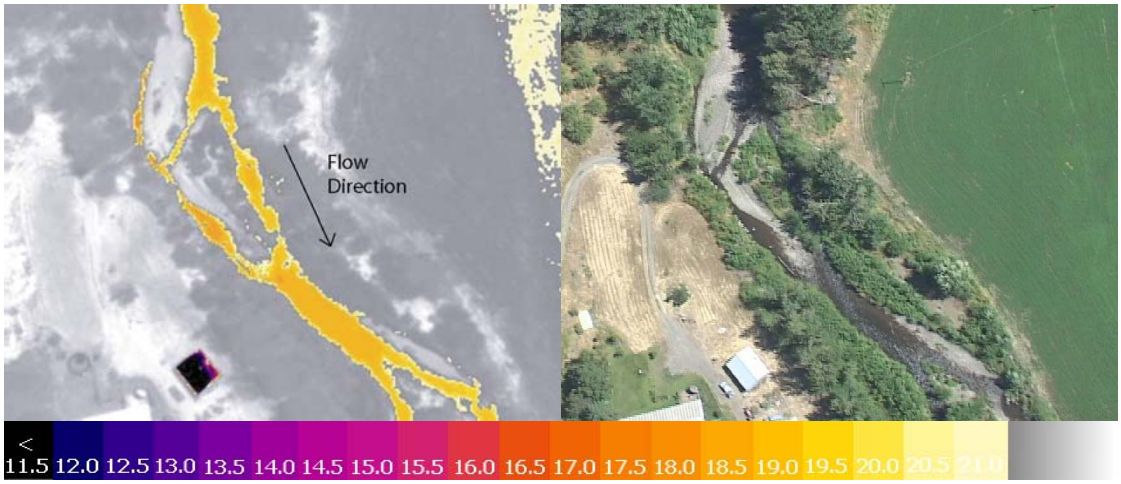


Figure 13 - TIR/color video image pair showing an apparent spring (17.8°C) on the right bank of the N.F. Touchet River (18.4°C) at river mile 1.4 (*frame: nftt0222*).

Wolf Creek

The median temperatures for each sampled image of the Wolf Creek were plotted versus the corresponding river mile (Figure 14). The plot also contains the median temperature of all surface water inflows (e.g. tributaries, surface springs, etc.) that were visible in the imagery labeled by river mile. Sampled surface water inflows are listed sequentially by river mile in Table 6.

At the upstream end of the survey, stream temperatures in Wolf Creek were ≈12.0°C. Wolf Creek warmed consistently in the downstream direction with water temperatures reaching near 18.0°C at the confluence of the NF Touchet River. As with the NF Touchet River, a number (7) of small springs and seeps were detected and sampled that create locally cool areas in the stream and contribute to the fine scale spatial thermal variability in the stream. The springs and seeps occur within the channel floodplain and suggest that hyporheic exchange as a source of cooling in the surveyed portion of Wolf Creek.

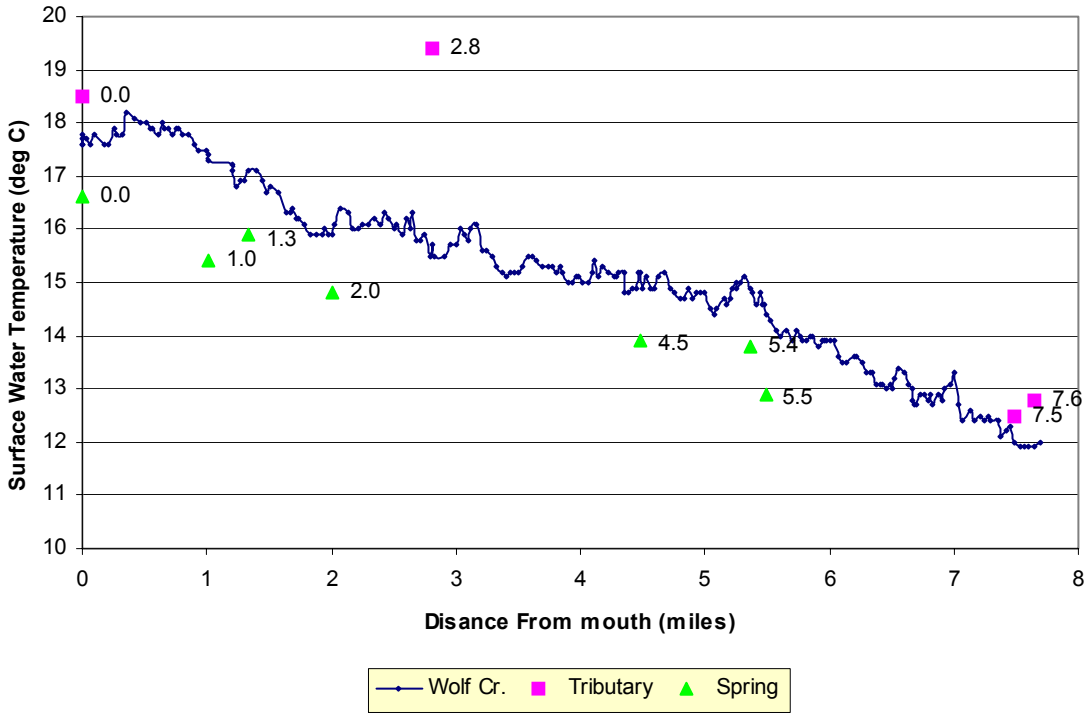


Figure 14 - Median channel temperatures versus river mile for the North Fork Touchet River, WA. Tributary and spring inflows are sampled by river mile.

Table 6 - Tributary temperatures for the Wolf Creek, WA. RB = Right Bank, LB = Left Bank looking downstream.

Tributary	Image	Km	Mile	Tributary °C	Wolf Cr. °C	Difference °C
North Fork Touchet (RB)	wlf0007	0.0	0.0	18.5	17.7	0.8
Spring (RB)	wlf0008	0.0	0.0	16.6	17.6	-1.0
Spring (LB)	wlf0074	1.6	1.0	15.4	17.4	-2.0
Spring (LB)	wlf0090	2.2	1.3	15.9	17.1	-1.2
Spring (RB)	wlf0130	3.2	2.0	14.8	15.9	-1.1
Robinson Creek (LB)	wlf0183	4.5	2.8	19.4	15.7	3.7
Spring (LB)	wlf0278	7.2	4.5	13.9	15.2	-1.3
Spring (LB)	wlf0330	8.6	5.4	13.8	14.9	-1.1
Spring (RB)	wlf0340	8.8	5.5	12.9	14.4	-1.5
Coates Creek (RB)	wlf0471	12.1	7.5	12.5	12.0	0.5
Whitney Creek (RB)	wlf0479	12.3	7.6	12.8	11.9	0.9

Discussion

TIR remote sensing surveys were successfully conducted on streams in the Walla Walla River Basin. Longitudinal temperature profiles were produced for each surveyed stream, which illustrate broad scale spatial temperature patterns and the location and influence of tributary and surface water inflows. This report presents the longitudinal temperature profiles and provides some hypotheses on the processes influencing spatial temperature patterns at this scale based on analysis of the TIR imagery and topographic base maps. Theses hypotheses are considered a starting point for more rigorous spatial analysis and fieldwork. Individual TIR and color video image frames are organized in an ArcView database to allow viewing temperature patterns and channel characteristics at finer spatial scales.

Comparison surface temperatures from the TIR images and kinetic temperatures recorded by in-stream data loggers showed that the radiant temperatures were on average within ±0.5°C, which was the specified tolerance for the survey. The in-stream data also provides a temporal context for assessing the spatial temperature patterns (Figures 15 and 16). On Mill Creek the flight timing was consistent with the daily maximum temperatures at all in-stream location and the radiant temperatures were slightly less than the kinetic temperatures for the three most downstream sensors. On the Touchet River, the flight timing was slightly prior to the recorded maximum daily stream temperature.

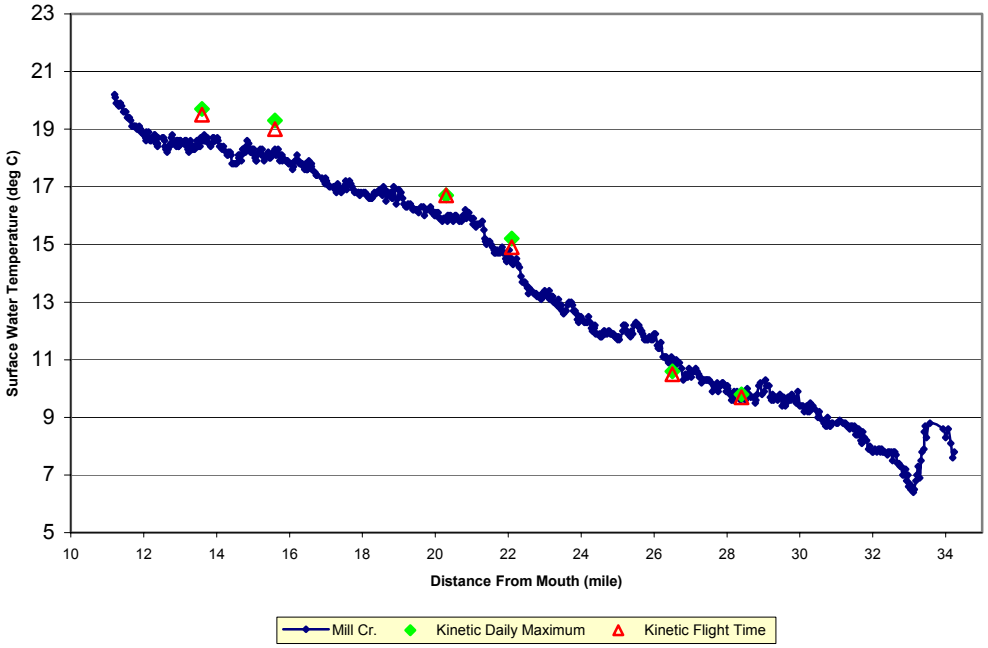


Figure 15 - Median temperatures in Mill Creek versus river miles. The plot shows location of in-stream sensors used to calibrate the TIR images with the recorded in-stream (kinetic) temperature at the time of the survey and recorded maximum temperature.

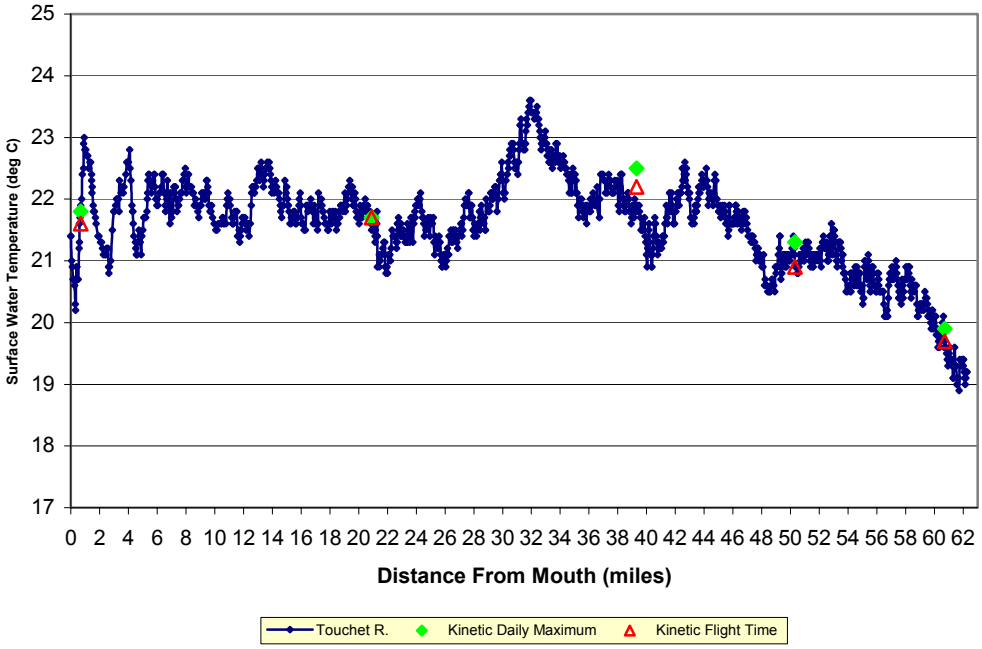


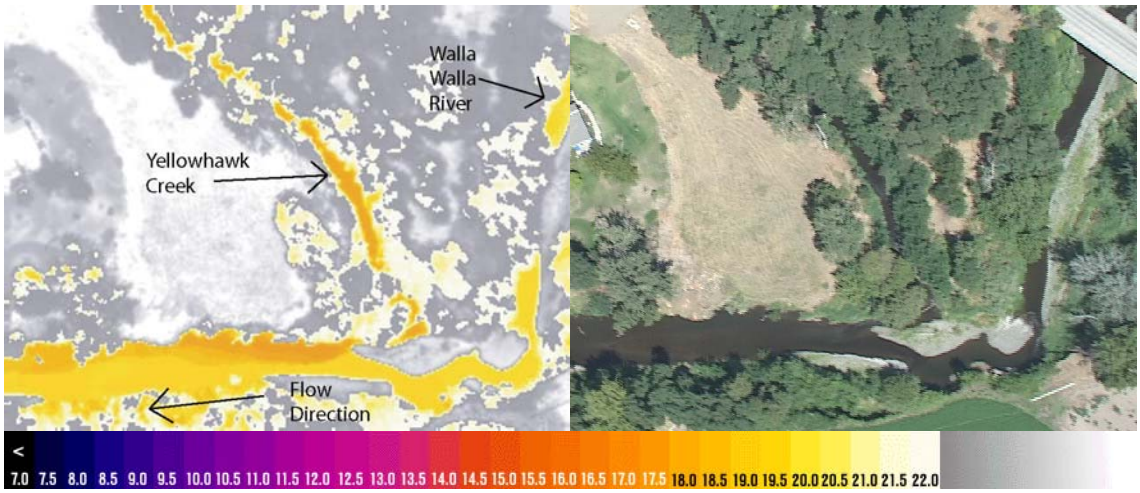
Figure 16 - Median temperatures in Touchet River versus river miles. The plot shows location of in-stream sensors used to calibrate the TIR images with the recorded in-stream (kinetic) temperature at the time of the survey and recorded maximum temperature.

Bibliography

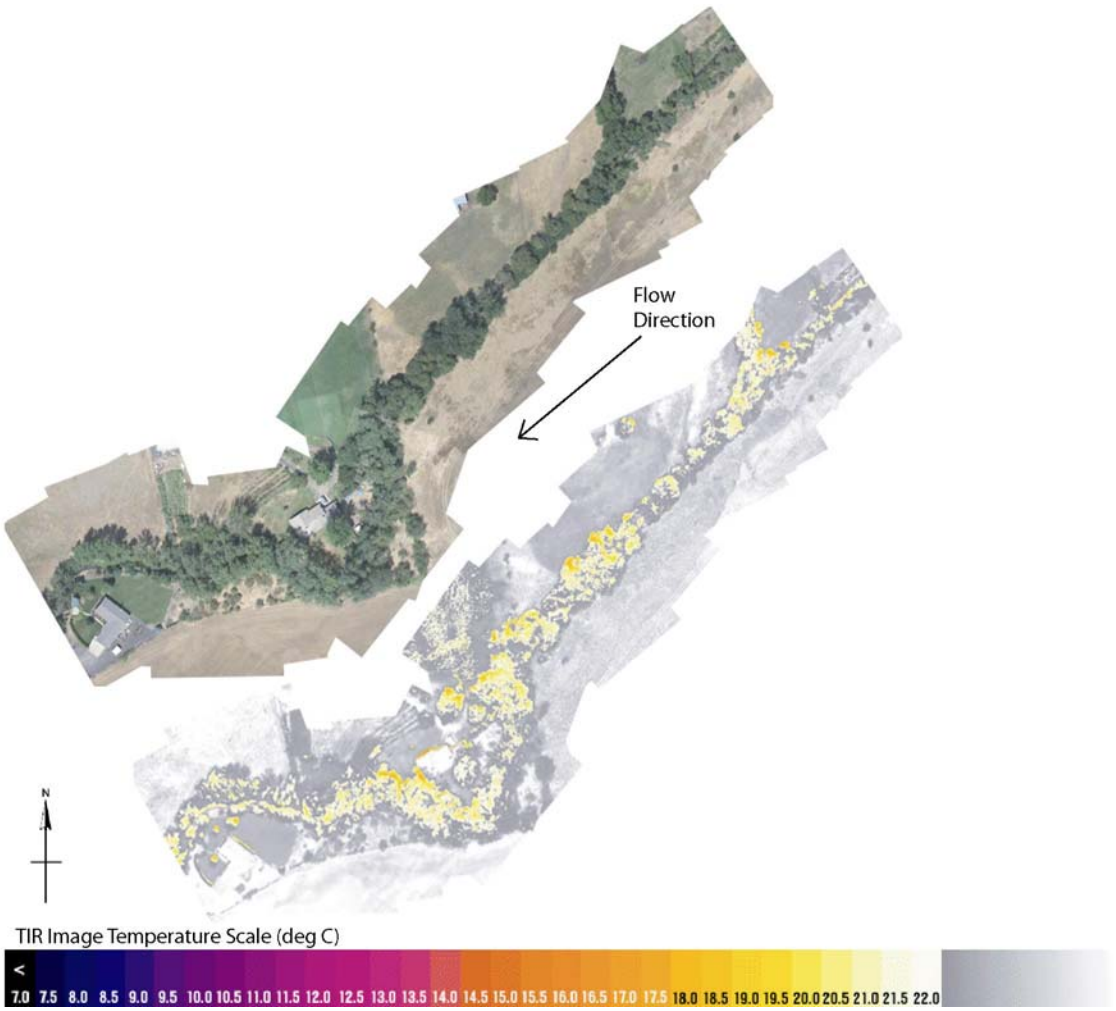
Torgersen, C.E., R. Faux, B.A. McIntosh, N. Poage, and D.J. Norton. 2001. Airborne thermal remote sensing for water temperature assessment in rivers and streams. *Remote Sensing of Environment* 76(3): 386-398.

Appendix A – Selected Images

Yellowhawk Creek

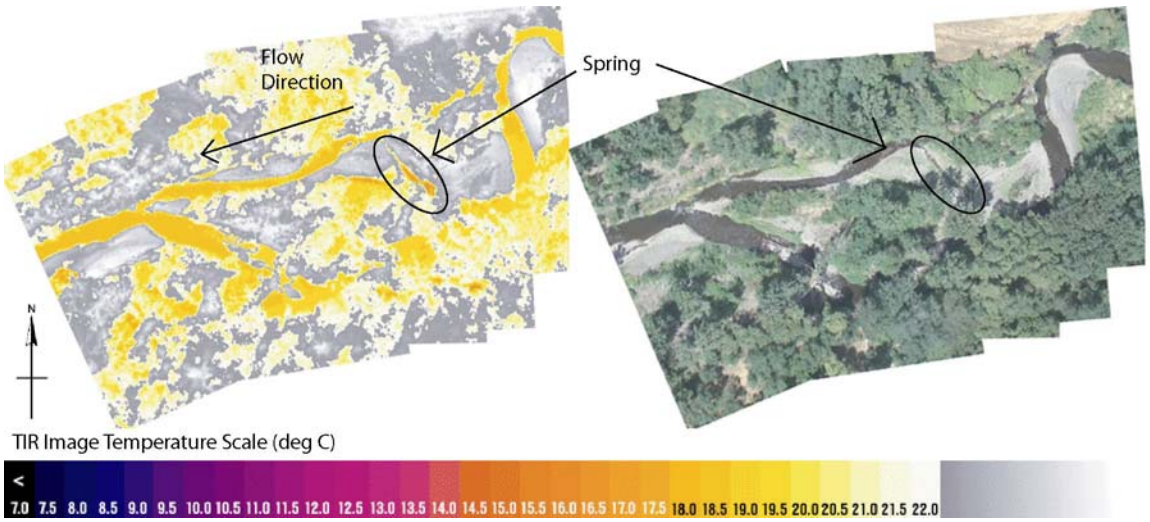


TIR/color video image pair showing the confluence of Yellowhawk Creek (17.3^{o}C) and the Walla Walla River (18.9^{o}) *(frame: yh0150).*

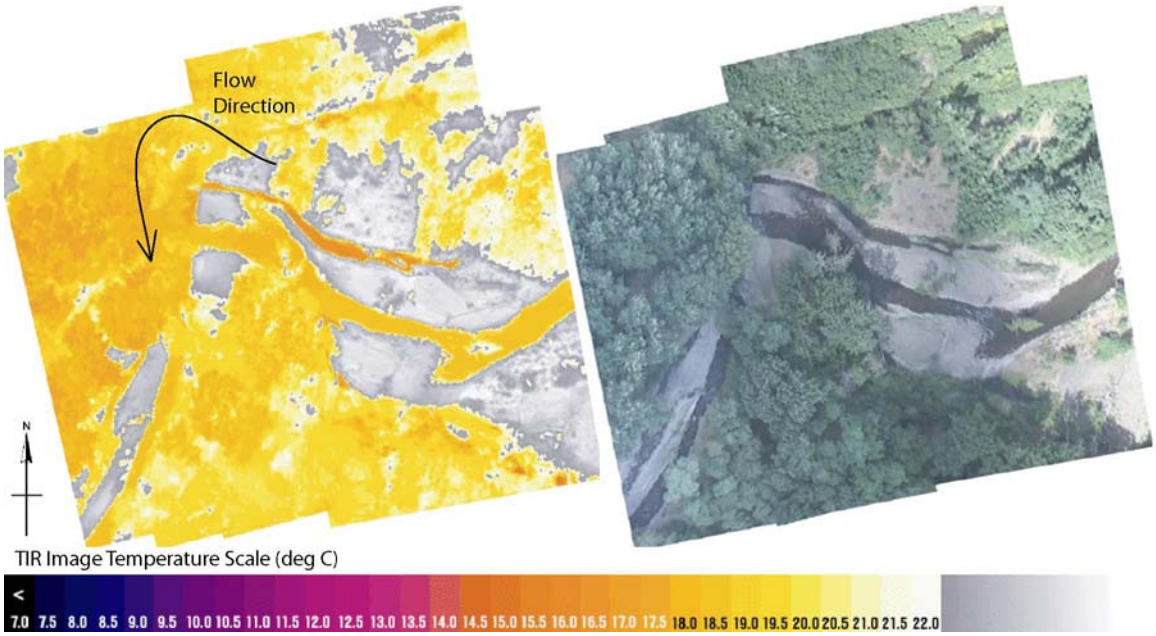


TIR/color video image pair showing a 0.4-mile section of Yellowhawk Creek that could not be sampled because canopy masks the stream surface *(frames: yh0715-0739).*

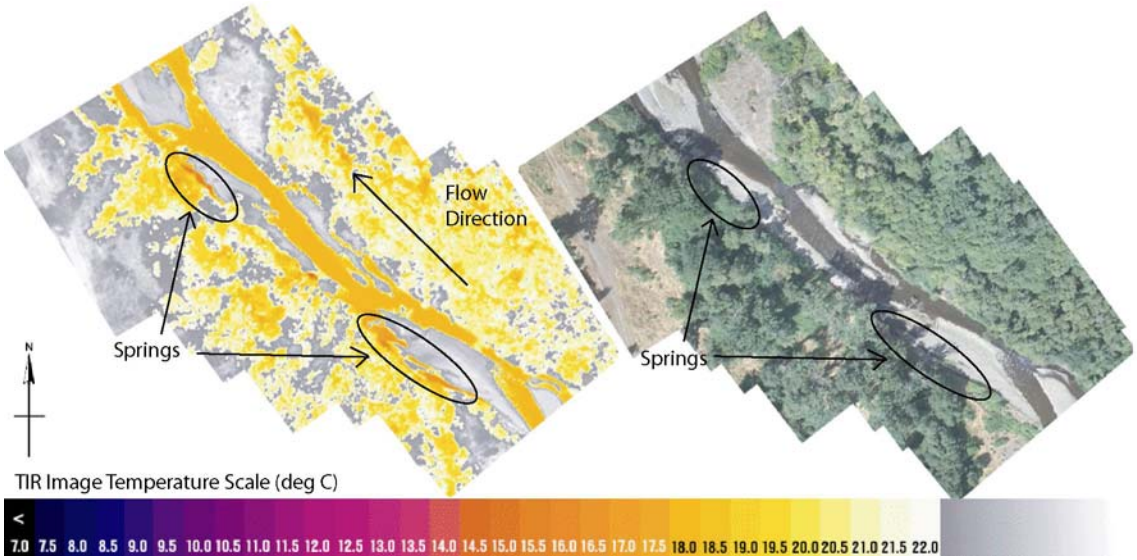
Mill Creek



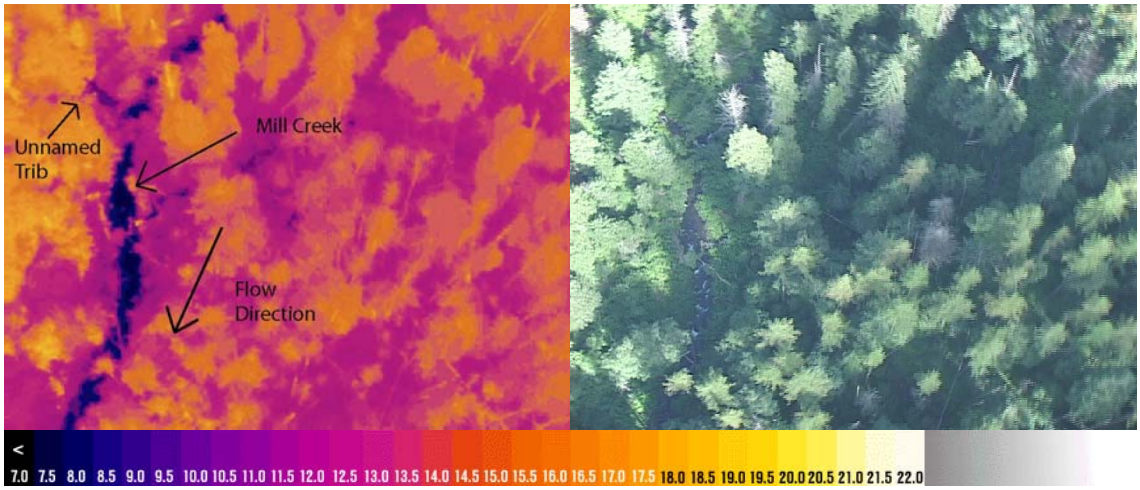
TIR/color video image pair showing a spring (16.6°C) along the left bank of the right bank side channel of Mill Creek (18.8°C) at river mile 13.5 *(frames: yh0947-0953).*



TIR/color video image pair showing a spring (16.4°C) on the right bank of Mill Creek (18.0°C) at river mile 14.7 *(frames: yh1064-1068).*

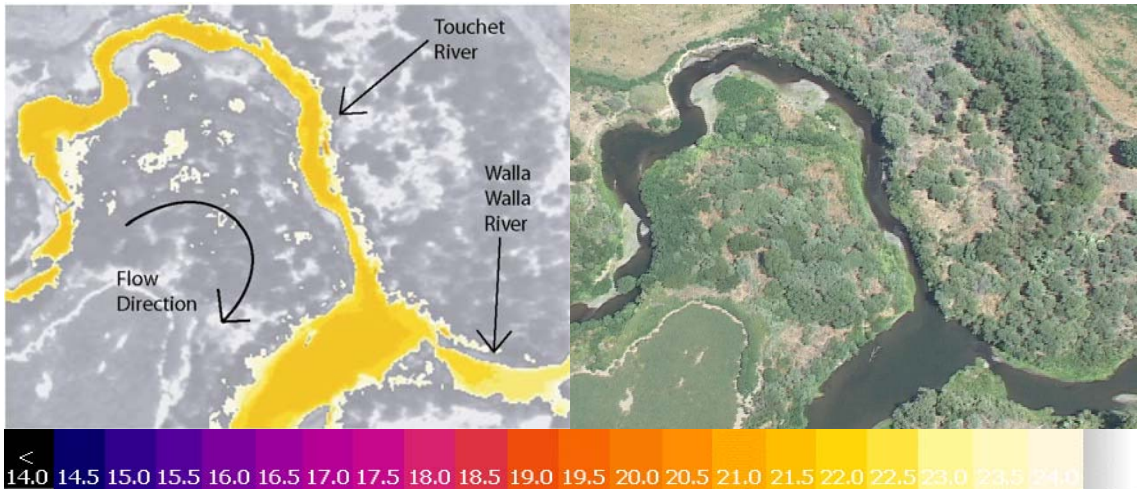


TIR/color video image pair showing a series of apparent springs along the left bank of Mill Creek (17.8°C) at river mile 16.0. The spring farthest downstream (at the top of the image) measures 15.3°C while the spring upstream measures 16.3°C *(frames: yh1175-1183).*

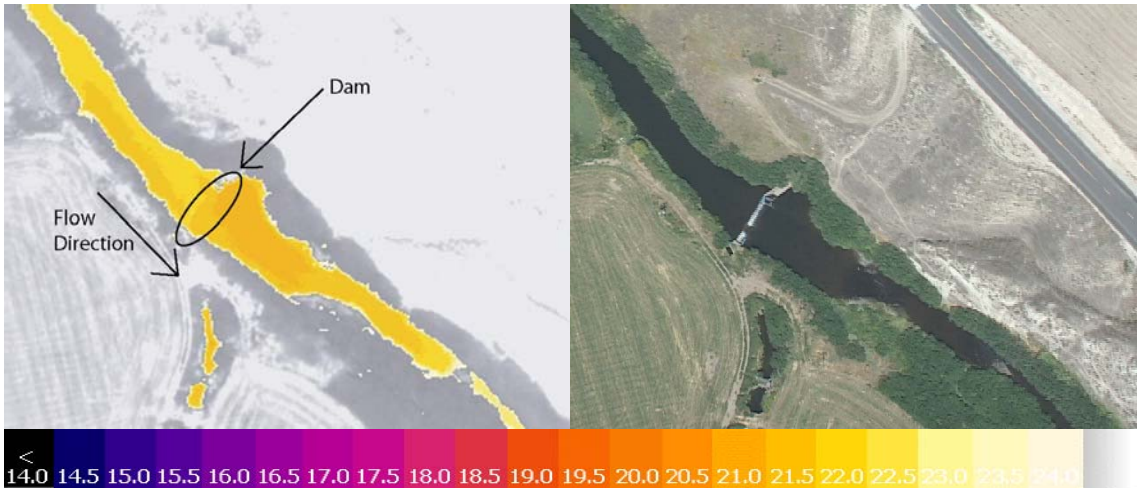


TIR/color video image pair showing the confluence of an unnamed tributary to the right bank of Mill Creek (7.8°C) at river mile 32.7 *(frame: yh2252).*

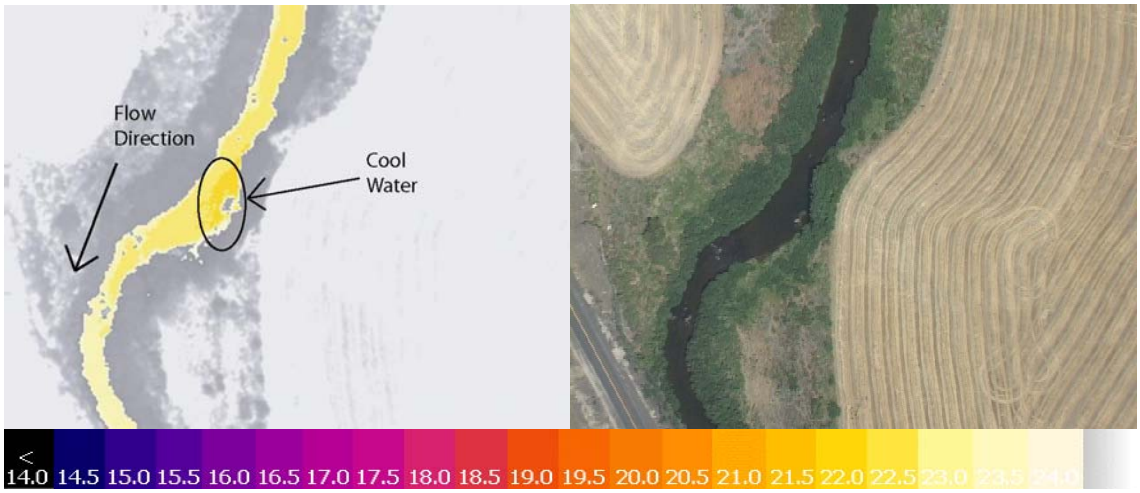
Touchet River



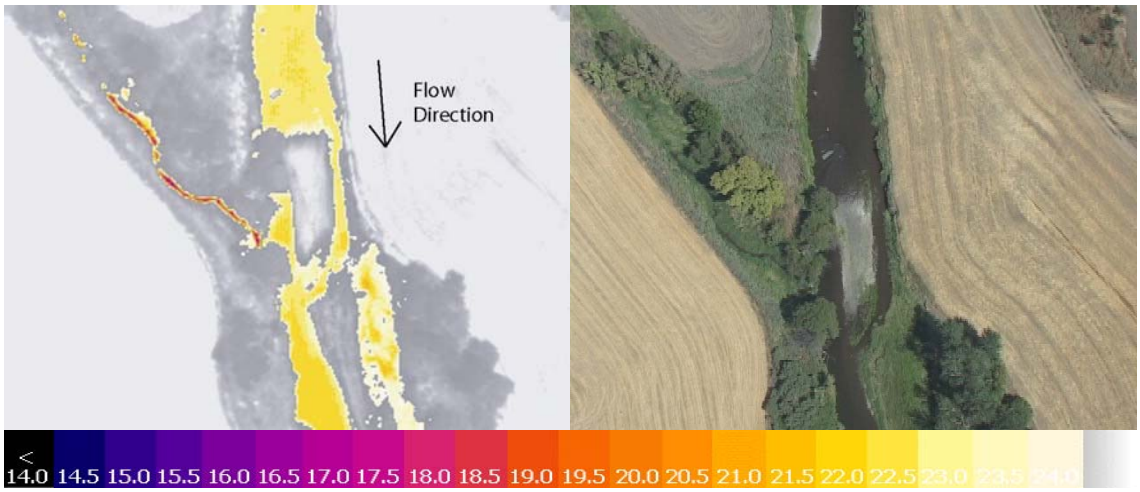
TIR/color video image pair showing the confluence of Touchet River (21.4°C) to the right bank of Walla Walla River (21.2°C) *(frame: touc0014).*



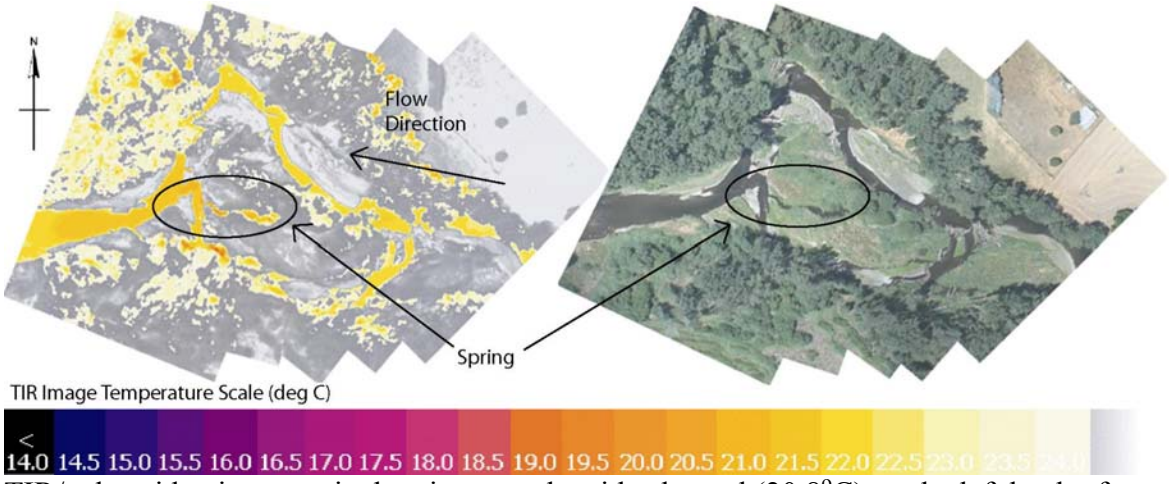
TIR/color video image pair showing possible stratification behind a diversion dam on the Touchet River at river mile 4.9. The temperature downstream is 20.8°C while the upstream temperature of the water is 21.5°C *(frame: touc0229).*



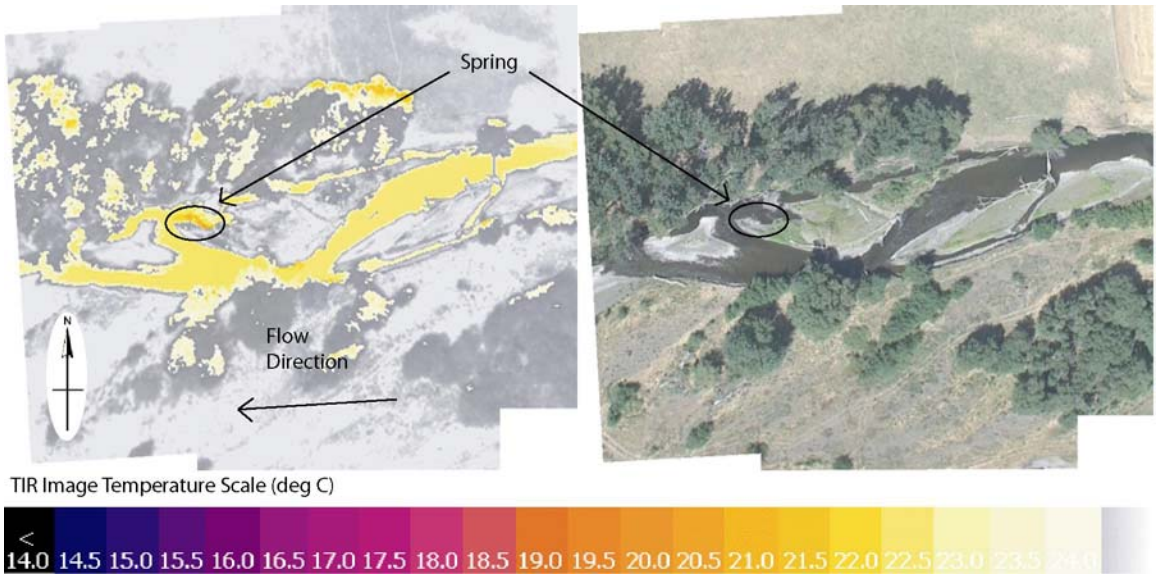
TIR/color video image pair showing an apparent cool water area (21.9°C) on the left bank of Touchet River (22.4°C) at river mile 13.3. The source of this cool area is unknown *(frame: touc0620).*



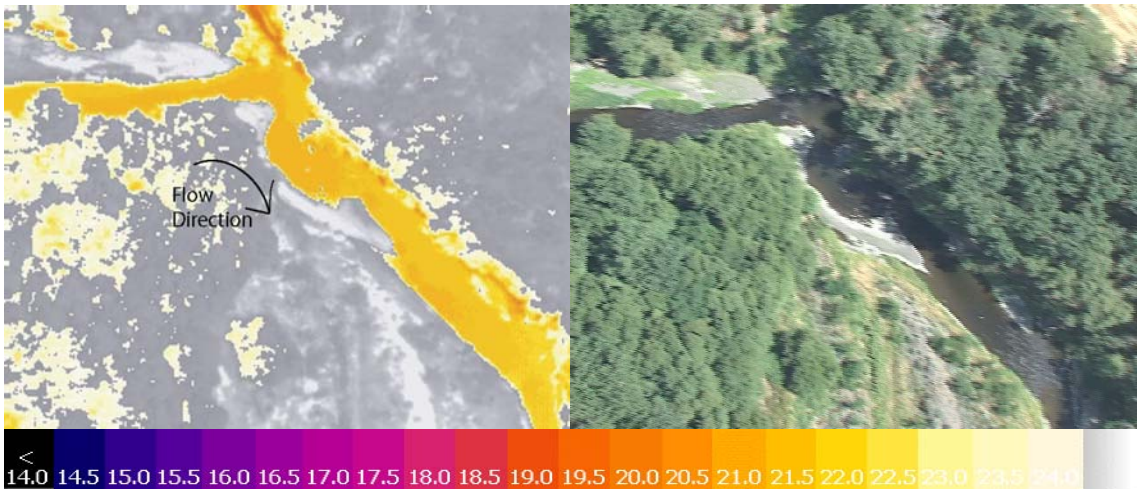
TIR/color video image pair showing the confluence of Whetstone Hollow Creek to the right bank of Touchet River (21.9°C) at river mile 39.4. Whetstone Hollow Creek was not sampled due to the lack of visibility in the image *(frame: touc1916).*



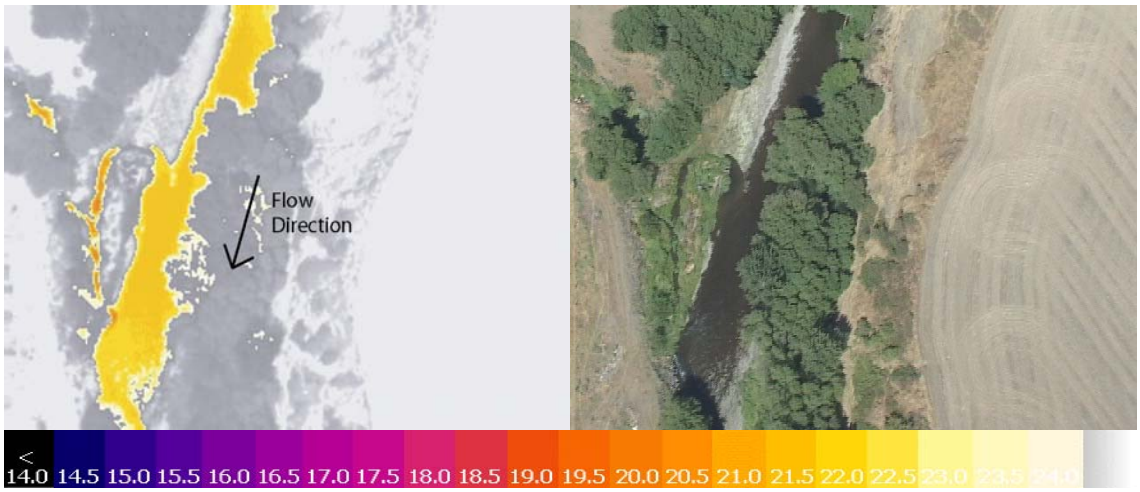
TIR/color video image pair showing a cooler side channel (20.8°C) on the left bank of Touchet River (21.4°C), which emerges within the stream channel at river mile 41.2 *(frames: touc2014-2019).*



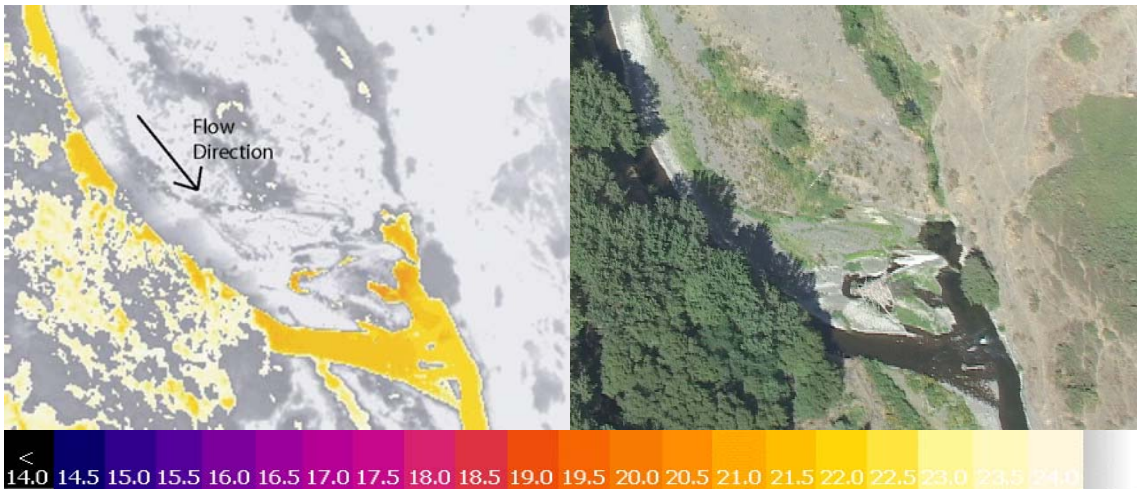
TIR/color video image pair showing a spring (20.4°C) in a side channel on the right bank of Touchet River (22.2°C) at river mile 43.9 *(frames: touc2154-2157).*



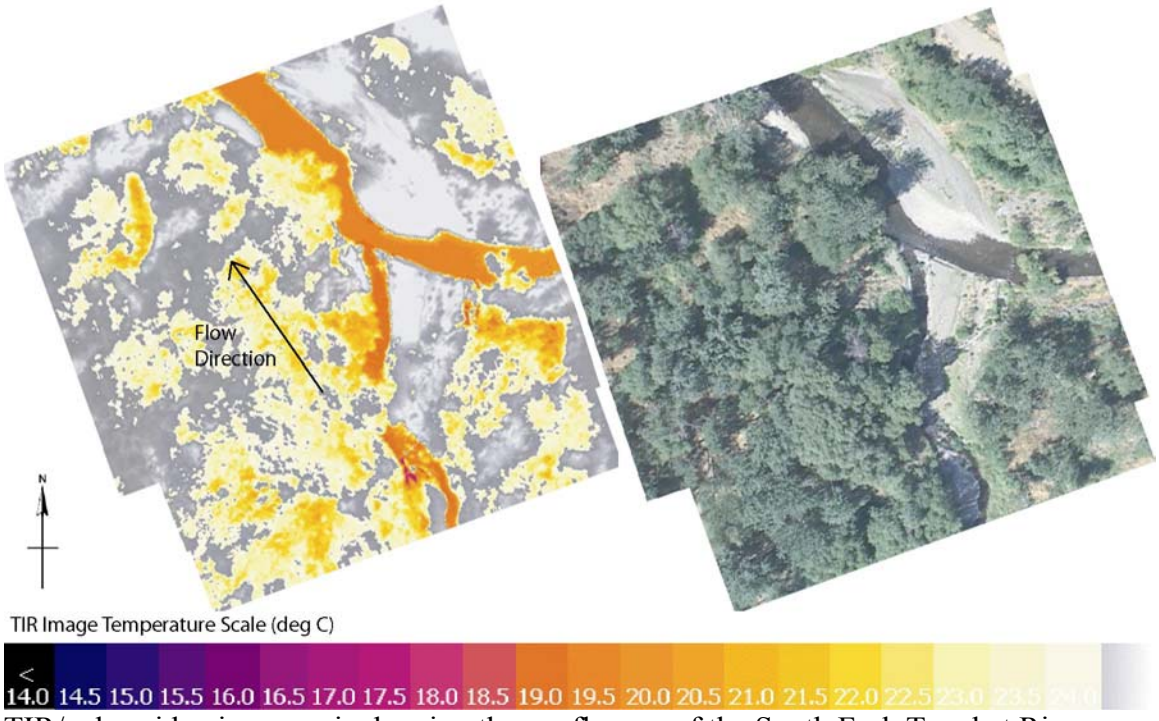
TIR/color video image pair showing the confluence of Coppei Creek (18.9°C) to the left bank of Touchet River (20.8°C) at river mile 49.0 *(frame: touc2402).*



TIR/color video image pair showing the presence of cooler water on the right bank of Touchet River (21.3°C) at river mile 53.1 *(frame: touc2629).*

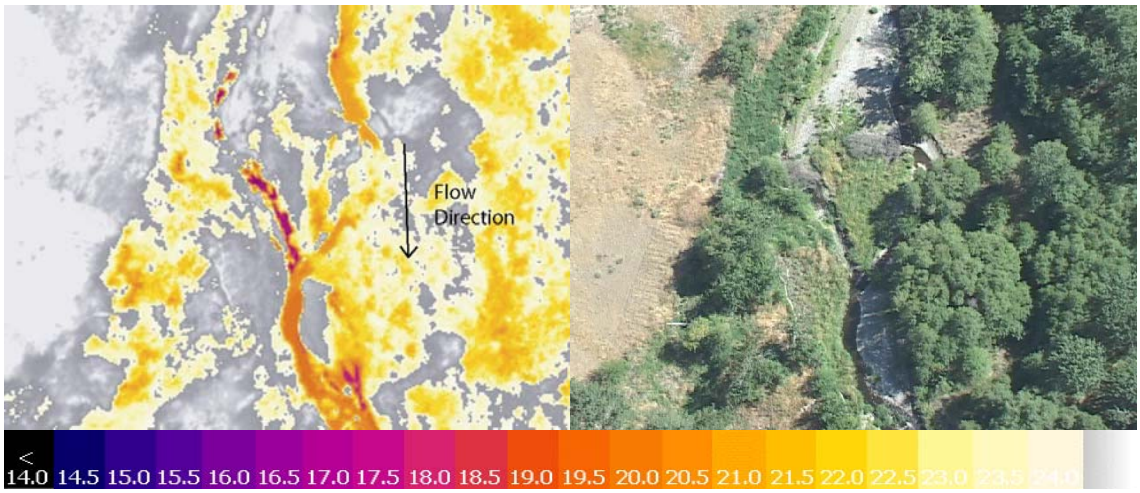


TIR/color video image pair showing a cool water seep along the left bank of Touchet River (21.3°C) at river mile 53.3 *(frame: touc2643).*



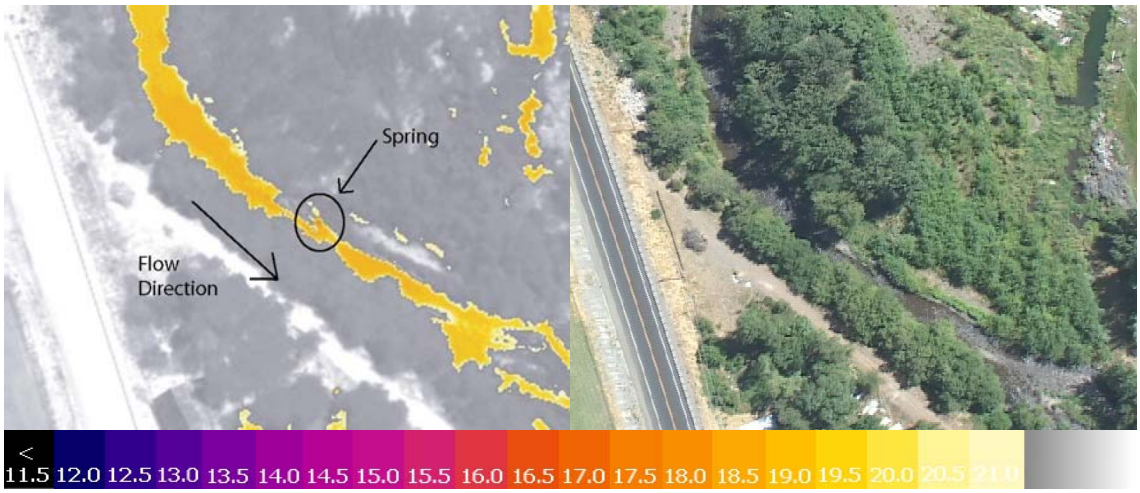
TIR/color video image pair showing the confluence of the South Fork Touchet River (18.8°C) and the North Fork Touchet River (19.2°C) on its left bank at river mile 62.3 *(frames: touc3108-3110).*

South Fork Touchet River

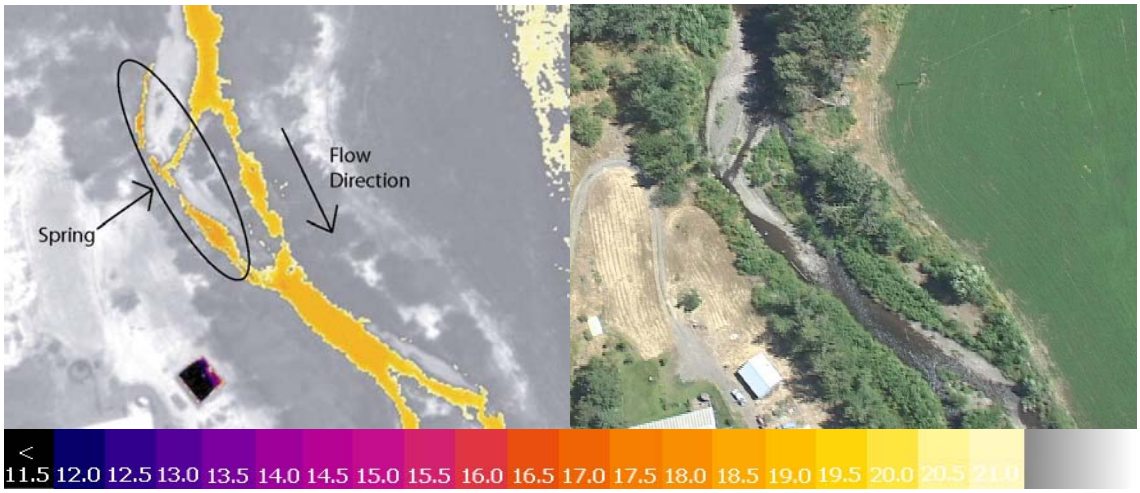


TIR/color video image pair showing a spring (16.4°C) on the right bank of the SF Touchet River (18.9°C) at river mile 0.1 *(frame: touc3114).*

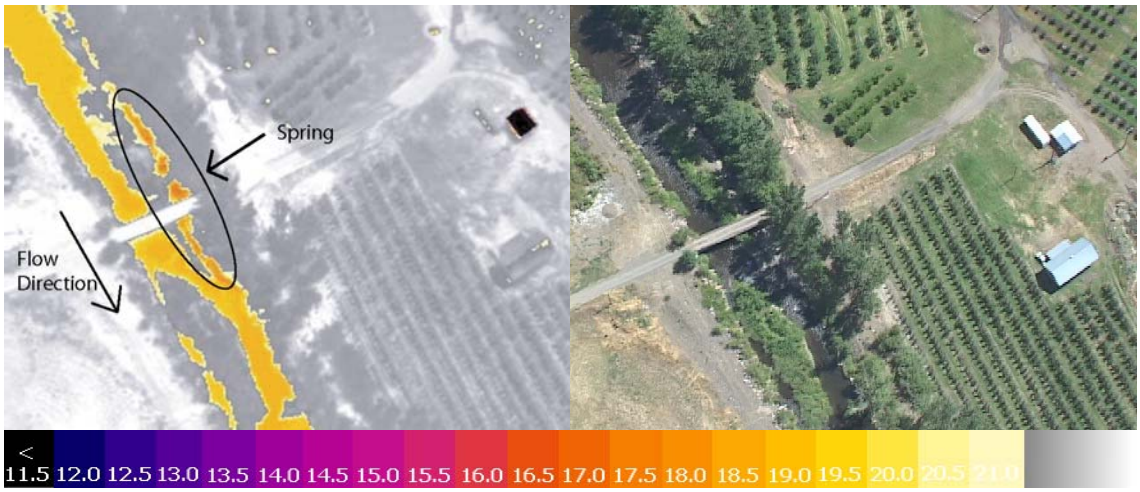
North Fork Touchet River



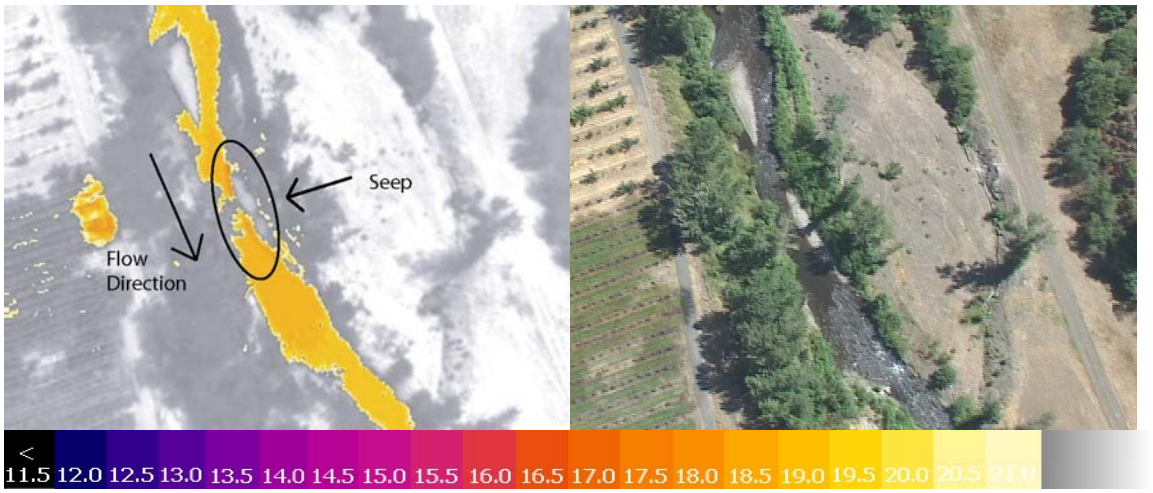
TIR/color video image pair showing a cool region, and therefore a possible spring, on the left bank of the NF Touchet River (18.3°C) at river mile 0.5 (*frame: nftt0178*).



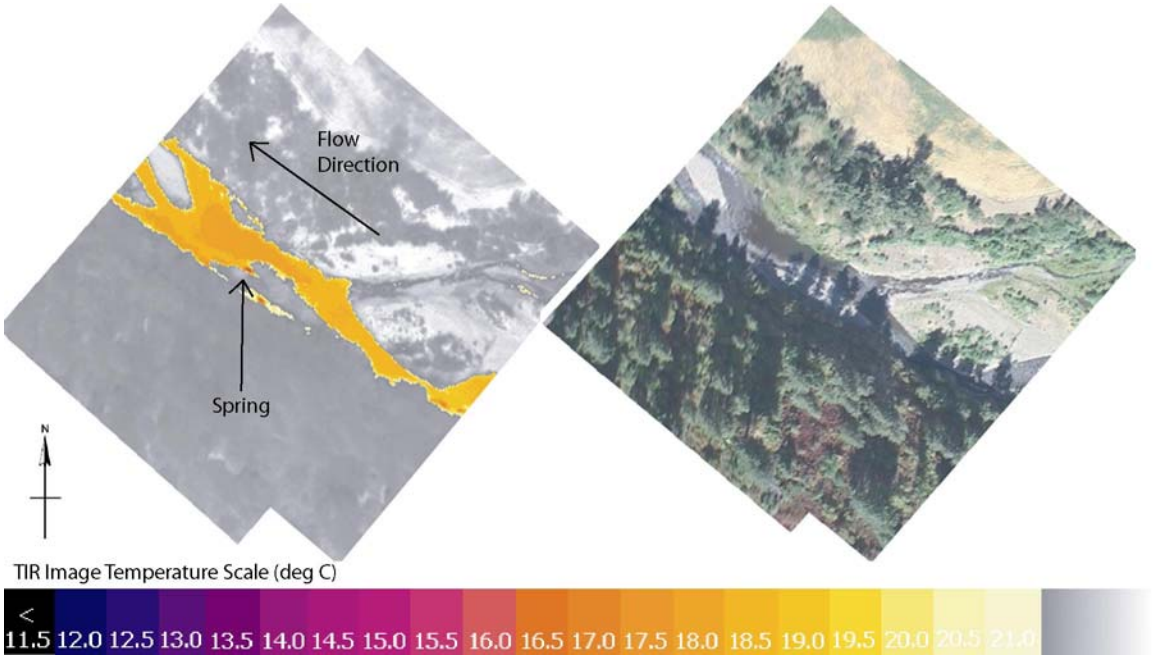
TIR/color video image pair showing a spring (17.8°C) on the right bank of the NF Touchet River (18.4°C) at river mile 1.4 (*frame: nftt0222*).



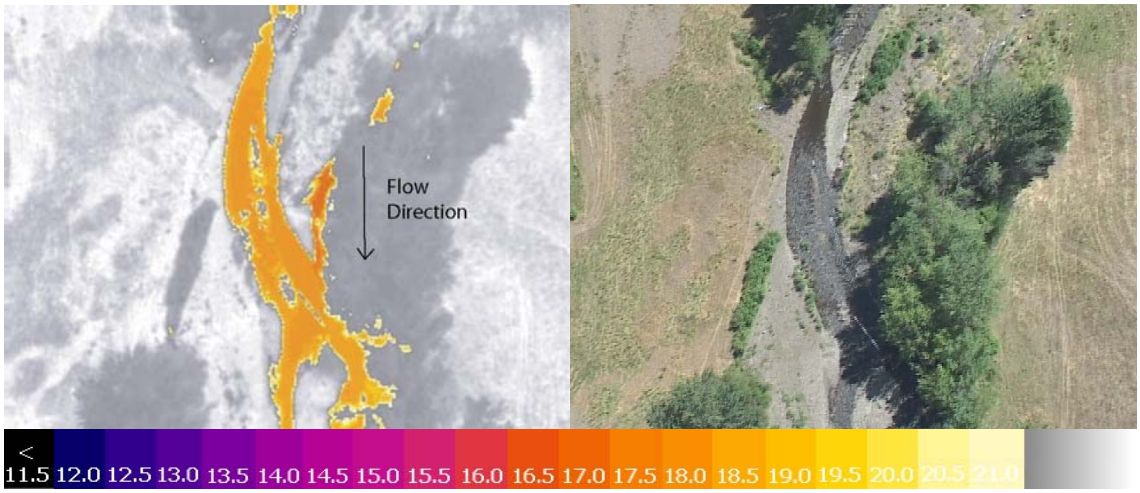
TIR/color video image pair showing a spring (16.8°C) located on the left bank of the NF Touchet River (18.4°C) at river mile 2.2 (*frame: nftt0261*).



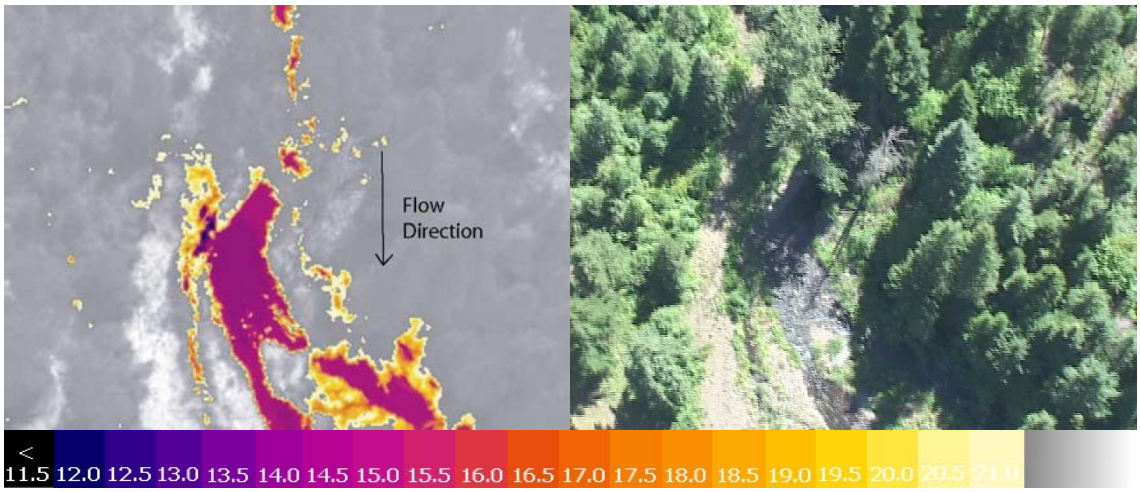
TIR/color video image pair showing a cold water seep (17.9°C) along the left bank of the NF Touchet River (18.4°C) at river mile 2.9 (*frame: nftt0293*).



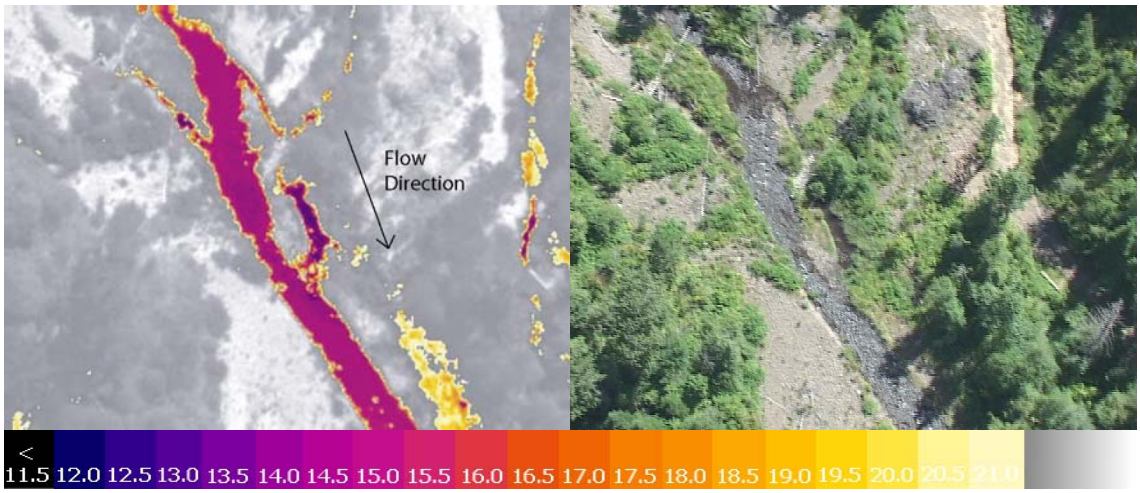
TIR/color video image pair showing a spring (15.9°C) along the left bank of the NF Touchet (17.9°C). Hatley Gulch is visible on the right bank looking downstream at river mile 3.3 (*frames: nftt0312-0313*).



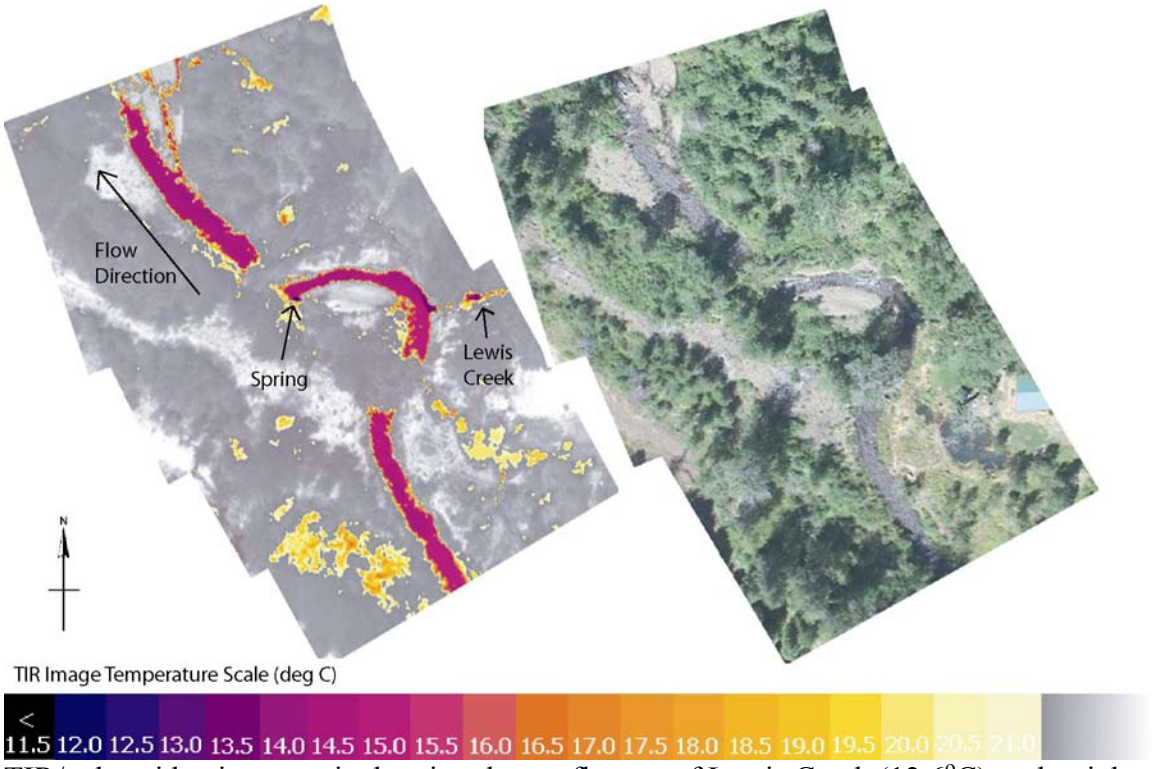
TIR/color video image pair showing a spring (16.4°C) on the left bank of NF Touchet River (17.3°C) at river mile 6.6 (*frame: nftt0485*).



TIR/color video image pair of a possible spring (11.9°C) on the right bank of the NF Touchet River (13.9°C) at river mile 11.0 (*frame: nftt0735*).

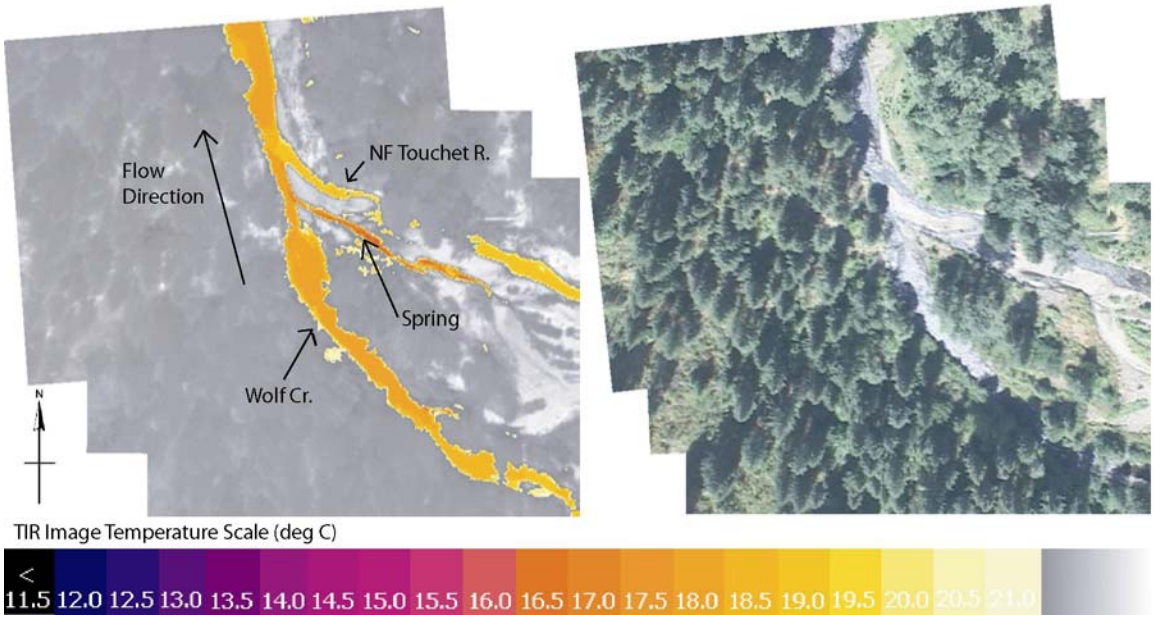


TIR/color video image pair showing a spring complex at river mile 11.1 of the NF Touchet River (14.4°C). The spring on the left bank (looking downstream) measured 12.9°C while the right bank spring was 12.7°C (*frame: nftt0740*).

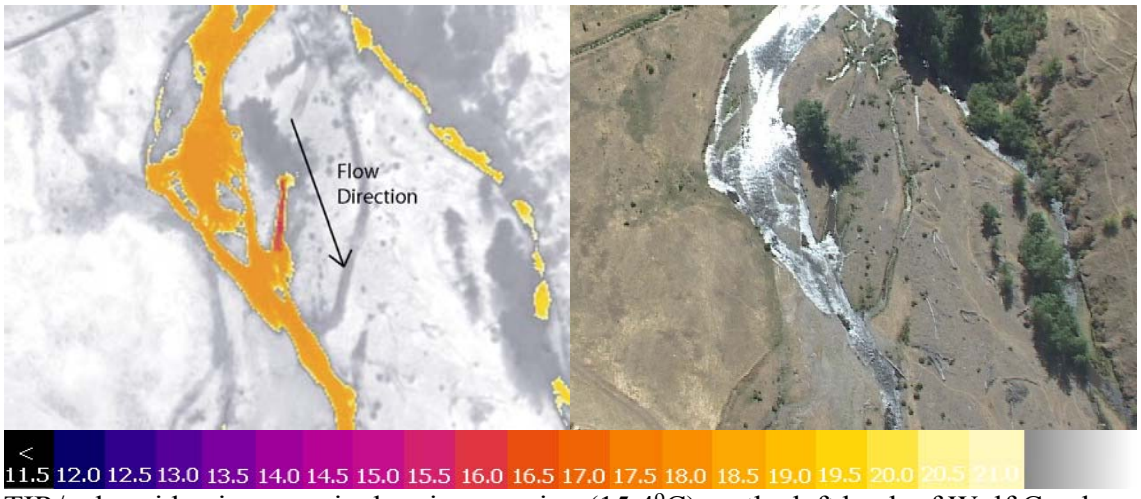


TIR/color video image pair showing the confluence of Lewis Creek (12.6°C) to the right bank of the NF Touchet River (14.6°C) just upstream of a left bank spring (11.7°C) at river mile 11.2 (*frames: nftt0743-0746*).

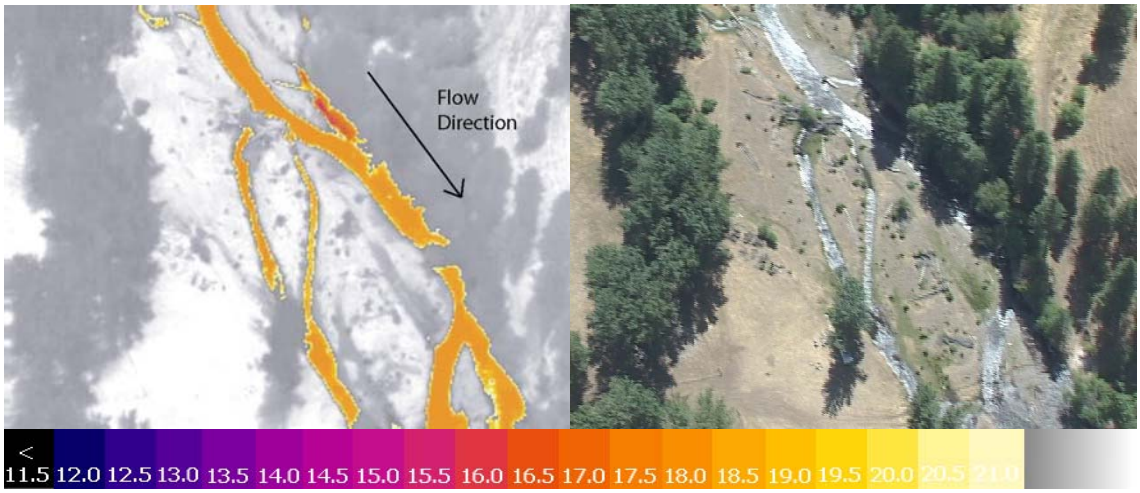
Wolf Creek



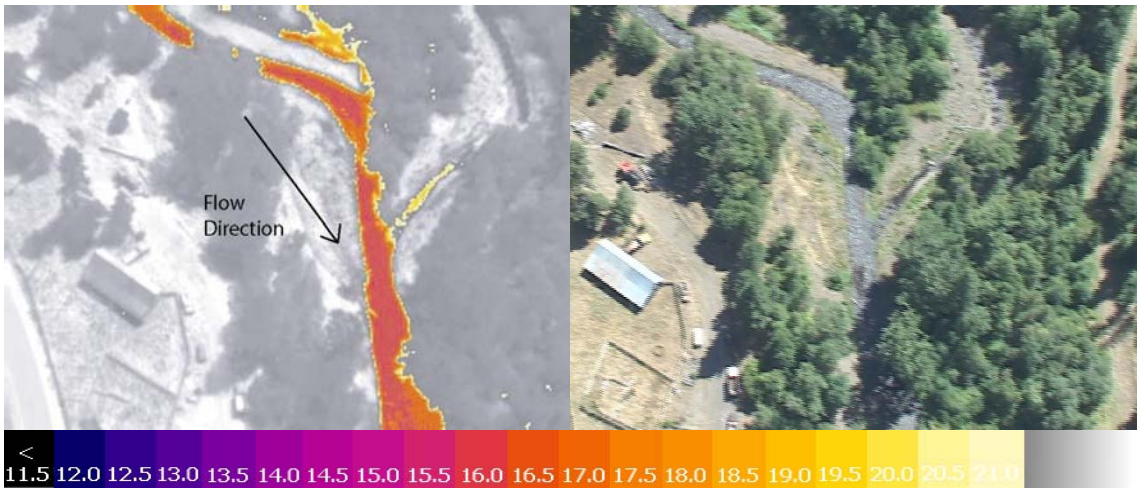
TIR/color video image pair showing a right bank spring (16.6°C) just upstream of the confluence of Wolf Creek to the left bank of the NF Touchet River (18.5°C (*frames: wlf0007-0009*).



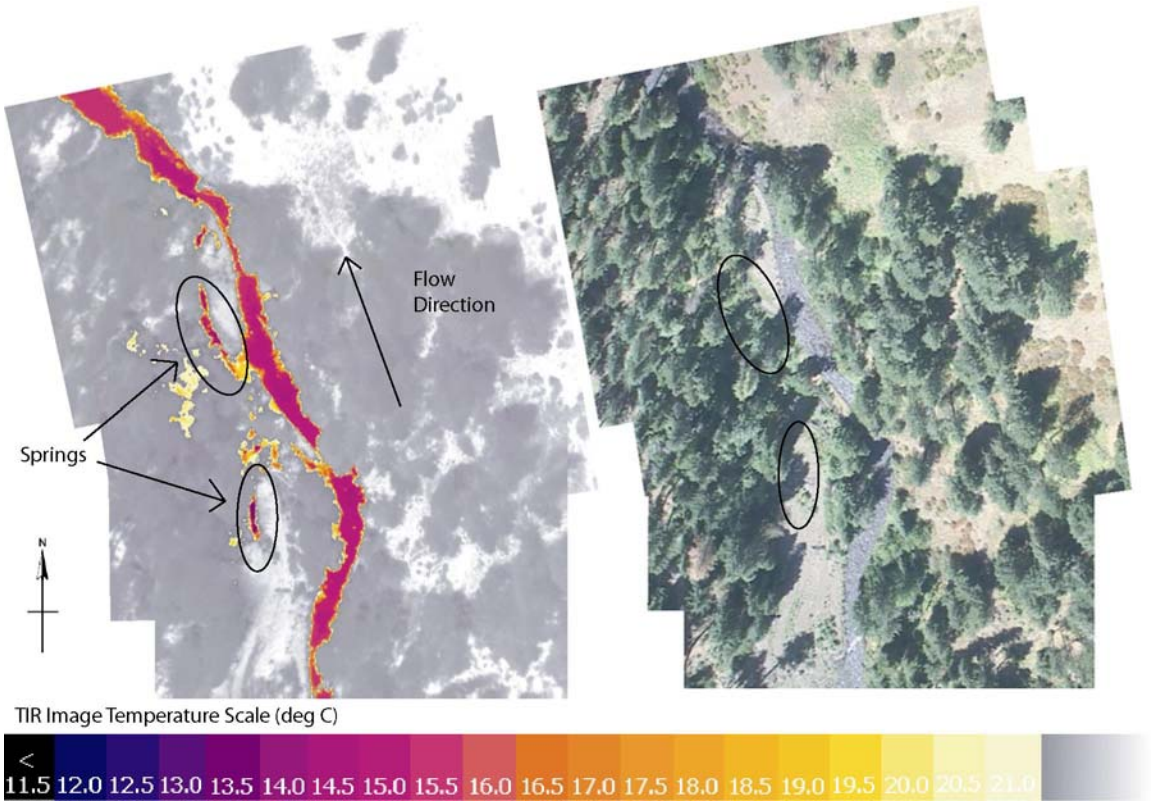
TIR/color video image pair showing a spring (15.4°C) on the left bank of Wolf Creek (17.4°C) at river mile 1.0 (*frame: wlf0074*).



TIR/color video image pair showing a spring (15.9°C) on the left bank of Wolf Creek (17.1°C) at river mile 1.3 (*frame: wlf0090*).



TIR/color video image pair showing the confluence of Robinson Creek (19.4°C) to the left bank of Wolf Creek (15.7°C) at river mile 2.8 (*frame: wlf0183*).



TIR/color video image pair showing a possible spring (13.8°C) on the left bank of Wolf Creek (14.9°C) at river mile 5.3 (*frames: wlf0330-0334*).